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Engine Horsepower Modeling for Diesel Engines

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16. ABSTRACT

The EPA is conducting a cycle development project for heavy duty engines. Ultimately the project will produce dynamometer cycles. The data being used in the cycle development data analyses are the data collected in the CAPE-21 survey. Forty-four trucks and three buses were surveyed in Los Angeles, and forty-four trucks and four buses were surveyed in New York City.

For the trucks surveyed, speed (MPH), engine rpm, road and traffic descriptions, and an engine load parameter (rail pressure for cummins diesel engines, rack position for Detroit Diesel Allison (DDA) diesel engines, throttle position for caterpillar diesel engines, and manifold vacuum for gasoline engines) were recorded at approximately one second intervals. For cycle development, it is desirable to have the load (power) parameter in terms of % engine HP. The purpose of this report is to summarize the analyses, subsequent results, and conclusions in developing a normalized horsepower model for diesel engines.

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Engine Horsepower Modeling for Diesel Engines

I. Introduction

The Emission Control Technology Division of EPA is currently conducting a cycle development project for heavy duty engines. Ultimately, this project will produce engine dynamometer cycles. The data being used in the cycle development data analyses are the data collected in the CAPE-21 survey. Forty-four (44) trucks and three (3) buses were surveyed in Los Angeles, and forty-four (44) trucks and four (4) buses were surveyed in New York City.

For the trucks surveyed, speed (MPH), engine rpm, road and traffic descriptions, and an engine load parameter (rail pressure for Cummins diesel engines, rack position for Detroit Diesel Allison (DDA) diesel engines, throttle position for Caterpillar diesel engines, and manifold vacuum for gasoline engines) were recorded at approximately one (1) second intervals. For cycle development, it is desirable to have the load (power) parameter in terms of % engine HP (normalized to maximum HP at each rpm).

The CAPE-21 trucks were calibrated on a chassis dynamometer. That is, various wheel horsepower levels were run at several different rpm values, and the load parameter was recorded for each operating point. Although the chassis dynamometer calibrations provided sufficient data to develop a horsepower model with % HP as a function of rpm and load parameter, the values used in developing a model of this sort would be wheel horsepower values. Thus, HP as predicted from this model would be actually engine horsepower minus drivetrain losses (transmission, axle, and tire losses). Since drivetrain losses are not linear nor accounted for, the wheel horsepower model's accuracy suffers. Consequently, another model would be desirable for predicting % engine horsepower.

The purpose of this report is to summarize the analyses, subsequent results, and conclusions in developing a normalized horsepower model for diesel engines. Cummins, DDA, and Caterpillar % horsepower models were developed independently. Therefore, this report body is structured with three distinct parts: Cummins, DDA, and Caterpillar diesel engines. Each part discusses the % horsepower development for each type of diesel separately.

II. Summary

Objective

The primary objective of the investigation as described in this report was to develop normalized engine horsepower models for the diesel engines tested in the CAPE-21 survey. These models would predict % engine HP knowing an rpm value and load factor value (rail pressure for Cummins diesel engines, rack travel for Detroit Diesel Allison diesel engines, and throttle position for Caterpillar diesel engines).

Results

For each engine make actual engine data, supplied by the manufacturers, was analyzed. From these analyses an analytical %HP model or an appropriate procedure for predicting %HP was developed. The analytical model or procedure for each engine make is summarized below.

Cummins diesel engines:

$$\% \text{ Horsepower} = 37.475\ (\% \text{ fuel pressure})^{.33} - 70.283$$

where % Horsepower and % fuel pressure are normalized to the maximum value at each rpm.

This equation is applicable to all Cummins diesel engines tested.

Detroit Diesel Allison diesel engines:

$$\% \text{ Horsepower} = -22.507\ (\log_{10}\text{RPM}) - .44802 \times 10^{-1}\ (\% \text{ rack travel}^{1.56})\ (\log_{10}\text{RPM}) + 173.90$$

where % horsepower is normalized to the maximum value at each rpm and % rack travel is normalized to the maximum value.

This equation is applicable to all Detroit Diesel engines tested.

Caterpillar diesel engines:

An adequate analytical expression for %HP could not be derived from the Caterpillar data. Therefore, matrices were constructed with % throttle and rpm on the axes and %HP in the body. Knowing a % throttle and rpm value, a %HP value can be read directly from the matrix. A separate matrix was developed for both Caterpillar diesel engines tested in the the CAPE-21 survey.

Conclusions and Recommendations

Each of the procedures for calculating %HP described above was derived from analysis of manufacturers' data and are only as good as the data used. An attempt was made to gather as much data for the analyses as possible. In some cases a complete data base was not obtainable. Consequently, some degree of engineering judgement was used in developing the %HP prediction procedure particularly in deciding to apply the models to diesel engines surveyed in CAPE-21 for which data was lacking. However, the %HP prediction procedures selected for use were considered the most accurate and the best approaches for arriving at % horsepower.

In conclusion, the three procedures for calculating %HP listed above are recommended for use in converting load factor to % engine horsepower. The procedure for each make is applicable to all engines of that make surveyed in the CAPE-21 project.

III. Cummins Diesel Engine Horsepower Model Development

A. Introduction

The first step taken in developing an accurate % hp model(s) for the Cummins diesel engines was to analyze actual engine data. The data used for this analysis was supplied by the Cummins Engine Co. Specifically, EPA engineers asked the Cummins Engine Co. for fuel pressure versus horsepower data for the Cummins diesel engines tested in the Los Angeles and New York surveys. Table 1 describes these engines. Table 2 summarizes the engine data that the Cummins Engine Co. provided. Figure 1 shows the NTC-335 data plotted. The data for the other engines have similar characteristic rail pressure versus torque curves.

Listed in Table 2 are data for five turbocharged, inline, six cylinder engines: NTC-290, NTC-335, NTC-350, NTC-230, and NTC-250. According to Cummins, these NTC engines are a representative cross section of the NT product line. Also included in Table 2 are data for two types of naturally aspirated small, diesel engines (V8-210 (V-504) and V-555) and one type of naturally aspirated medium, V-8 diesel engine (V-903). Unfortunately, Cummins could not provide EPA with data for all of the engines that were surveyed. However, Cummins' engineers did believe, with reasonable confidence, that all engines of a particular type should exhibit similar rail pressure (normalized) versus horsepower characteristics. For instance, a % power model developed for the NTC (turbocharged in-line six cylinder) engines, from the data in Table 2, would be applicable to all NTC in-line, six cylinder engines. The same can be said for the naturally aspirated small V-8's (V8-210 and V-555) and naturally aspirated medium V-8's (V-903). However, since the rated rpm values are different (2100 rpm for the in-line sixes, 3300 rpm for the small V-8's, and 2600 rpm for the medium V-8's) the data treatment and subsequent percent power models will necessarily be different.

The following data analysis summary is separated into three distinct sections: (1) in-line six cylinder engines (turbocharged) (2) small V-8 engines (naturally aspirated) and (3) medium V-8 engines (naturally aspirated). Analyses performed are quite similar. However, to prevent any confusion, they are discussed separately.

B. Data Analyses

1. In-Line, Six Cylinder Diesel Engines (Turbocharged)

Multiple, stepwise regressions were performed on each set of engine data, and on all of the data combined. Percent engine power

Table 1

Cummins Diesel Engines

Los Angeles Survey

Truck No.	Engine
20	NTC-350 (cut to NTC-335) (6 cyl)
31	NH-220 (6 cyl)
34	NTC-290 (6 cyl)
37	NTC-335 (6 cyl)
38	NH-250 (6 cyl)
44	NHC-250 (6 cyl)
46	NH-220 (6 cyl)
80	V-903 (8 cyl)

New York City Survey

Truck No.	Engine
27	NH-230 (6 cyl)
34	CF-160 (6 cyl)
36	NH3-180 (6 cyl)
37	V8-210 (8 cyl)
43	NHCT-CT (6 cyl)
53	NH-180 (6 cyl)
54	NHCT-CT (6 cyl)
57	NTC-350 (6 cyl)
60	NH-855 (6 cyl)
62	NH-180 (6 cyl)
65	NHE-195 (6 cyl)

NTC-290

TABLE 2

CODE	ENGINE RPM	FUEL (RAIL) PRESSURE (PSI)	% POWER (NORMALIZED TO MAXIMUM HORSEPOWER AT EACH RPM)	% FUEL PRES (NORMALIZED TO MAXIMUM FUEL PRES.)	% FUEL PRES (NORMALIZED TO MAXIMUM FUEL PRES. AT EACH RPM)
1	1200.	81.0	100.0	50.0	100.0
1	1200.	63.0	89.3	38.9	77.8
1	1200.	50.0	79.8	30.9	61.7
1	1200.	32.0	60.1	19.8	39.5
1	1200.	20.0	39.9	12.3	24.7
1	1500.	108.0	100.0	66.7	100.0
1	1500.	89.0	89.8	54.9	82.4
1	1500.	74.0	79.1	45.7	68.5
1	1500.	49.0	59.9	30.2	45.4
1	1500.	30.0	40.1	18.5	27.8
1	1800.	145.0	100.0	89.5	100.0
1	1800.	120.0	90.2	74.1	82.8
1	1800.	97.0	79.9	59.9	66.9
1	1800.	65.0	59.8	40.1	44.8
1	1800.	38.0	40.2	23.5	26.2
1	1950.	144.0	100.0	88.9	100.0
1	1950.	120.0	89.9	74.1	83.3
1	1950.	96.0	78.6	59.3	66.7
1	1950.	65.0	59.7	40.1	45.1
1	1950.	40.0	40.3	24.7	27.8
1	2100.	162.0	100.0	100.0	100.0
1	2100.	137.0	90.2	84.6	84.6
1	2100.	115.0	79.7	71.0	71.0
1	2100.	80.0	60.1	49.4	49.4
1	2100.	48.0	39.9	29.6	29.6
1	2300.	162.0	100.0	100.0	100.0
1	2300.	136.0	89.0	84.0	84.0
1	2300.	118.0	79.4	72.8	72.8
1	2300.	80.0	59.6	49.4	49.4
1	2300.	50.0	39.7	30.9	30.9

NTC-335

TABLE 2

CODE	ENGINE RPM	FUEL (RAIL) PRESSURE (PSI)	% POWER (NORMALIZED TO MAXIMUM HORSEPOWER AT EACH RPM)	% FUEL PRES (NORMALIZED TO MAXIMUM FUEL PRES.)	% FUEL PRES (NORMALIZED TO MAXIMUM FUEL PRES. AT EACH RPM)
2	1000.	46.0	100.0	23.7	100.0
2	1000.	35.0	85.7	18.0	76.1
2	1000.	26.0	71.4	13.4	56.5
2	1000.	19.0	57.1	9.8	41.3
2	1000.	14.0	42.9	7.2	30.4
2	1200.	73.0	100.0	37.6	100.0
2	1200.	56.0	86.3	28.9	76.7
2	1200.	41.0	71.7	21.1	56.2
2	1200.	30.0	58.3	15.5	41.1
2	1200.	22.0	45.0	11.3	30.1
2	1500.	124.0	100.0	63.9	100.0
2	1500.	95.0	86.5	49.0	76.6
2	1500.	73.0	73.0	37.6	58.9
2	1500.	55.0	59.6	28.4	44.4
2	1500.	39.0	46.2	20.1	31.5
2	1800.	166.0	100.0	85.6	100.0
2	1800.	129.0	87.3	66.5	77.7
2	1800.	105.0	74.8	54.1	63.3
2	1800.	80.0	62.4	41.2	48.2
2	1800.	58.0	49.9	29.9	34.9
2	1950.	183.0	100.0	94.3	100.0
2	1950.	149.0	88.1	76.8	81.4
2	1950.	118.0	75.7	60.8	64.5
2	1950.	88.0	63.3	45.4	48.1
2	1950.	61.0	50.8	31.4	33.3
2	2100.	194.0	100.0	100.0	100.0
2	2100.	158.0	87.7	81.4	81.4
2	2100.	126.0	75.2	64.9	64.9
2	2100.	97.0	62.6	50.0	50.0
2	2100.	71.0	50.1	36.6	36.6

NTC-350

TABLE 2

CODE	ENGINE RPM	FUEL (RAIL) PRESSURE (PSI)	% POWER (NORMALIZED TO MAXIMUM HORSEPOWER AT EACH RPM)	% FUEL PRES (NORMALIZED TO MAXIMUM FUEL PRES.)	% FUEL PRES (NORMALIZED TO MAXIMUM FUEL PRES. AT EACH RPM)
3	1100.	60.0	100.0	31.6	100.0
3	1100.	48.0	90.4	25.3	80.0
3	1100.	40.0	80.1	21.1	66.7
3	1100.	25.0	60.2	13.2	41.7
3	1100.	14.0	38.0	7.4	23.3
3	1300.	102.0	100.0	53.7	100.0
3	1300.	82.0	90.1	43.2	80.4
3	1300.	64.0	80.2	33.7	62.7
3	1300.	41.0	60.4	21.6	40.2
3	1300.	24.0	40.6	12.6	23.5
3	1500.	127.0	100.0	66.8	100.0
3	1500.	106.0	90.6	55.8	83.5
3	1500.	87.0	80.2	45.8	68.5
3	1500.	53.0	60.4	27.9	41.7
3	1500.	32.0	40.1	16.8	25.2
3	1800.	140.0	100.0	73.7	100.0
3	1800.	115.0	89.8	60.5	82.1
3	1800.	90.0	80.6	47.4	64.3
3	1800.	62.0	60.2	32.6	44.3
3	1800.	39.0	39.8	20.5	27.9
3	1950.	165.0	100.0	86.8	100.0
3	1950.	137.0	90.4	72.1	83.0
3	1950.	113.0	80.7	59.5	68.5
3	1950.	72.0	59.9	37.9	43.6
3	1950.	44.0	39.6	23.2	26.7
3	2100.	187.0	100.0	98.4	100.0
3	2100.	148.0	88.1	77.9	79.1
3	2100.	126.0	78.8	66.3	67.4
3	2100.	81.0	58.0	42.6	43.3
3	2100.	49.0	39.4	25.8	26.2
3	2300.	190.0	100.0	100.0	100.0
3	2300.	158.0	90.0	83.2	83.2
3	2300.	134.0	80.0	70.5	70.5
3	2300.	85.0	60.0	44.7	44.7
3	2300.	53.0	40.0	27.9	27.9

TABLE 2

NTC-230

CODE	ENGINE RPM	FUEL (RAIL) PRESSURE (PSI)	% POWER (NORMALIZED TO MAXIMUM HORSEPOWER AT EACH RPM)	% FUEL PRES (NORMALIZED TO MAXIMUM FUEL PRES.)	% FUEL PRES (NORMALIZED TO MAXIMUM FUEL PRES. AT EACH RPM)
4	1100.	76.0	100.0	48.4	100.0
4	1100.	68.0	94.6	43.3	89.5
4	1100.	46.0	75.0	29.3	60.5
4	1100.	26.0	50.0	16.6	34.2
4	1100.	19.0	39.9	12.1	25.0
4	1300.	99.0	100.0	63.1	100.0
4	1300.	67.0	79.0	42.7	67.7
4	1300.	37.0	52.7	23.6	37.4
4	1300.	27.0	42.0	17.2	27.3
4	1500.	90.0	100.0	57.3	100.0
4	1500.	83.0	95.0	52.9	92.2
4	1500.	58.0	75.0	36.9	64.4
4	1500.	33.0	50.0	21.0	36.7
4	1500.	25.0	40.0	15.9	27.8
4	1600.	135.0	100.0	86.0	100.0
4	1600.	124.0	94.9	79.0	91.9
4	1600.	85.0	75.0	54.1	63.0
4	1600.	48.0	50.0	30.6	35.6
4	1600.	36.0	39.8	22.9	26.7
4	1800.	131.0	100.0	83.4	100.0
4	1800.	124.0	96.4	79.0	94.7
4	1800.	87.0	75.8	55.4	66.4
4	1800.	50.0	50.8	31.8	38.2
4	1800.	38.0	40.3	24.2	29.0
4	1900.	134.0	100.0	85.4	100.0
4	1900.	124.0	95.2	79.0	92.5
4	1900.	89.0	75.2	56.7	66.4
4	1900.	54.0	50.0	34.4	40.3
4	1900.	40.0	40.4	25.5	29.9
4	2100.	139.0	100.0	88.5	100.0
4	2100.	129.0	95.1	82.2	92.8
4	2100.	94.0	75.5	59.9	67.6
4	2100.	56.0	50.6	35.7	40.3
4	2100.	44.0	40.4	28.0	31.7
4	2300.	157.0	100.0	100.0	100.0
4	2300.	147.0	95.3	93.6	93.6
4	2300.	107.0	75.3	68.2	68.2
4	2300.	64.0	50.2	40.8	40.8
4	2300.	50.0	40.0	31.8	31.8

NTC-250

TABLE 2

CODE	ENGINE RPM	FUEL (RAIL) PRESSURE (PSI)	% POWER (NORMALIZED TO MAXIMUM HORSEPOWER AT EACH RPM)	% FUEL PRES (NORMALIZED TO MAXIMUM FUEL PRES.)	% FUEL PRES (NORMALIZED TO MAXIMUM FUEL PRES. AT EACH RPM)
5	1200.	82.0	100.0	46.6	100.0
5	1200.	66.0	89.7	37.5	80.5
5	1200.	55.0	79.9	31.3	67.1
5	1200.	35.0	59.8	19.9	42.7
5	1200.	21.0	40.2	11.9	25.6
5	1400.	113.0	100.0	64.2	100.0
5	1400.	91.0	89.1	51.7	80.5
5	1400.	74.0	78.7	42.0	65.5
5	1400.	48.0	58.8	27.3	42.5
5	1400.	28.0	39.8	15.9	24.8
5	1500.	127.0	100.0	72.2	100.0
5	1500.	106.0	90.0	60.2	83.5
5	1500.	86.0	79.6	48.9	67.7
5	1500.	56.0	60.0	31.8	44.1
5	1500.	32.0	40.0	18.2	25.2
5	1800.	141.0	100.0	80.1	100.0
5	1800.	118.0	89.9	67.0	83.7
5	1800.	98.0	79.8	55.7	69.5
5	1800.	64.0	59.9	36.4	45.4
5	1800.	38.0	40.1	21.6	27.0
5	1950.	146.0	100.0	83.0	100.0
5	1950.	123.0	90.0	69.9	84.2
5	1950.	104.0	80.0	59.1	71.2
5	1950.	68.0	60.0	38.6	46.6
5	1950.	42.0	40.0	23.9	28.8
5	2100.	161.0	100.0	91.5	100.0
5	2100.	137.0	90.0	77.8	85.1
5	2100.	114.0	80.0	64.8	70.8
5	2100.	77.0	60.0	43.8	47.8
5	2100.	47.0	40.0	26.7	29.2
5	2300.	176.0	100.0	100.0	100.0
5	2300.	148.0	89.5	84.1	84.1
5	2300.	127.0	80.1	72.2	72.2
5	2300.	86.0	60.1	48.9	48.9
5	2300.	52.0	39.9	29.5	29.5

TABLE 2

V8-210 (V-504)

CODE	ENGINE RPM	FUEL (RAIL) PRESSURE (PSI)	% POWER (NORMALIZED TO MAXIMUM HORSEPOWER AT EACH RPM)	% FUEL PRES (NORMALIZED TO MAXIMUM FUEL PRES.)	% FUEL PRES (NORMALIZED TO MAXIMUM FUEL PRES. AT EACH RPM)
6	1200.	41.0	100.0	28.5	100.0
6	1200.	34.0	95.3	23.6	82.9
6	1200.	30.0	89.4	20.8	73.2
6	1200.	26.0	84.7	18.1	63.4
6	1200.	24.0	80.0	16.7	58.5
6	1200.	21.0	75.3	14.6	51.2
6	1200.	20.0	70.6	13.9	48.8
6	1900.	77.0	100.0	53.5	100.0
6	1900.	68.0	96.4	47.2	88.3
6	1900.	57.0	91.4	39.6	74.0
6	1900.	49.0	85.0	34.0	63.6
6	1900.	43.0	80.0	29.9	55.8
6	1900.	40.0	75.7	27.8	51.9
6	1900.	34.0	70.0	23.6	44.2
6	2500.	106.0	100.0	73.6	100.0
6	2500.	95.0	96.5	66.0	89.6
6	2500.	81.0	90.6	56.3	76.4
6	2500.	72.0	86.5	50.0	67.9
6	2500.	62.0	80.1	43.1	58.5
6	2500.	57.0	76.6	39.6	53.8
6	2500.	49.0	70.8	34.0	46.2
6	3000.	132.0	100.0	91.7	100.0
6	3000.	118.0	95.8	81.9	89.4
6	3000.	100.0	89.5	69.4	75.8
6	3000.	89.0	84.2	61.8	67.4
6	3000.	79.0	80.0	54.9	59.8
6	3000.	70.0	74.7	48.6	53.0
6	3000.	61.0	69.5	42.4	46.2
6	3300.	144.0	100.0	100.0	100.0
6	3300.	132.0	96.4	91.7	91.7
6	3300.	113.0	90.8	78.5	78.5
6	3300.	100.0	85.7	69.4	69.4
6	3300.	89.0	80.6	61.8	61.8
6	3300.	80.0	75.0	55.6	55.6
6	3300.	70.0	69.9	48.6	48.6

TABLE 2

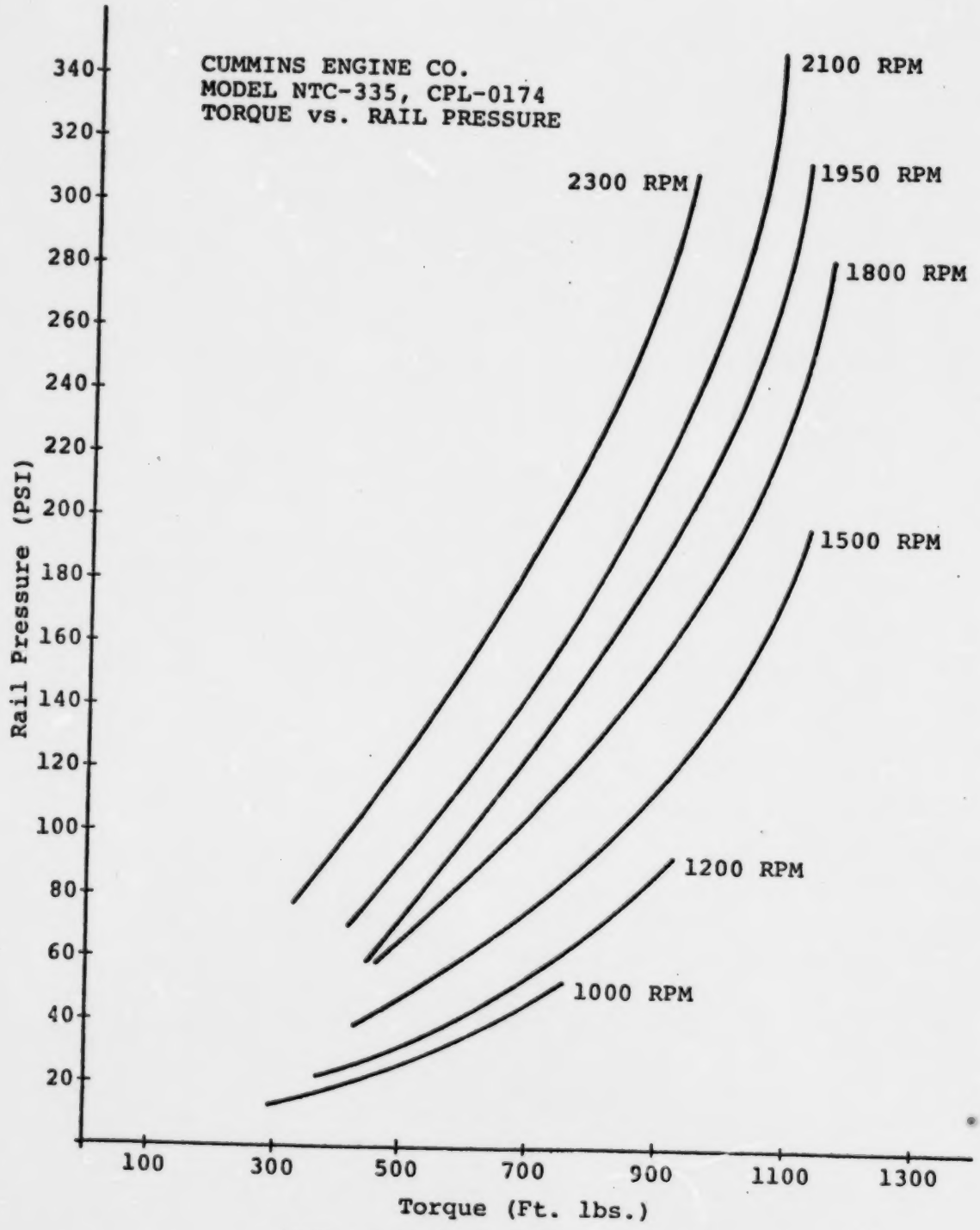
CODE	ENGINE RPM	FUEL (RAIL) PRESSURE (PSI)	% POWER (NORMALIZED TO MAXIMUM HORSEPOWER AT EACH RPM)	% FUEL PRES (NORMALIZED TO MAXIMUM FUEL PRES.)	% FUEL PRES (NORMALIZED TO MAXIMUM FUEL PRES. AT EACH RPM)
7	1500.	47.0	100.0	30.1	100.0
7	1500.	39.0	91.4	25.0	83.0
7	1500.	34.0	83.6	21.8	72.3
7	1500.	29.0	75.9	18.6	61.7
7	1500.	25.0	68.1	16.0	53.2
7	1500.	21.0	59.5	13.5	44.7
7	1500.	18.0	51.7	11.5	38.3
7	1800.	61.0	100.0	39.1	100.0
7	1800.	51.0	91.5	32.7	83.6
7	1800.	43.0	83.1	27.6	70.5
7	1800.	37.0	75.4	23.7	60.7
7	1800.	31.0	67.6	19.9	50.8
7	1800.	27.0	59.2	17.3	44.3
7	1800.	22.0	51.4	14.1	36.1
7	2100.	79.0	100.0	50.6	100.0
7	2100.	63.0	90.3	40.4	79.7
7	2100.	51.0	80.0	32.7	64.6
7	2100.	41.0	69.7	26.3	51.9
7	2100.	33.0	60.0	21.2	41.8
7	2100.	27.0	50.9	17.3	34.2
7	2400.	99.0	100.0	63.5	100.0
7	2400.	79.0	90.3	50.6	79.8
7	2400.	63.0	80.1	40.4	63.6
7	2400.	50.0	69.9	32.1	50.5
7	2400.	40.0	60.2	25.6	40.4
7	2400.	32.0	50.0	20.5	32.3
7	2400.	24.0	40.3	15.4	24.2
7	2400.	18.0	30.1	11.5	18.2
7	2400.	13.0	20.4	8.3	13.1
7	2400.	8.0	10.2	5.1	8.1
7	2400.	5.0	1.6	3.2	5.1
7	2700.	119.0	100.0	76.3	100.0
7	2700.	95.0	90.6	60.9	79.8
7	2700.	75.0	80.2	48.1	63.0
7	2700.	60.0	69.8	38.5	50.4
7	2700.	47.0	59.9	30.1	39.5
7	2700.	37.0	50.0	23.7	31.1
7	2700.	28.0	39.6	17.9	23.5
7	2700.	21.0	29.7	13.5	17.6
7	2700.	15.0	19.8	9.6	12.6
7	2700.	10.0	9.4	6.4	8.4
7	2700.	6.0	1.5	3.8	5.0
7	3000.	137.0	100.0	87.8	100.0
7	3000.	112.0	91.0	71.8	81.8
7	3000.	90.0	81.0	57.7	65.7
7	3000.	72.0	70.6	46.2	52.6
7	3000.	57.0	60.7	36.5	41.6
7	3000.	45.0	50.7	28.8	32.8
7	3000.	34.0	40.8	21.8	24.8

TABLE 2

7	3000.	26.0	30.8	16.7	19.0
7	3000.	18.0	20.4	11.5	13.1
7	3000.	13.0	10.4	8.3	9.5
7	3000.	8.0	1.9	5.1	5.8
7	3300.	156.0	100.0	100.0	100.0
7	3300.	126.0	90.8	80.8	80.8
7	3300.	102.0	80.6	65.4	65.4
7	3300.	83.0	70.5	53.2	53.2
7	3300.	67.0	60.4	42.9	42.9
7	3300.	52.0	50.2	33.3	33.3
7	3300.	41.0	40.1	26.3	26.3
7	3300.	32.0	30.4	20.5	20.5
7	3300.	23.0	20.3	14.7	14.7
7	3300.	20.0	10.1	12.8	12.8
7	3300.	11.0	1.8	7.1	7.1

TABLE 2

CODE	ENGINE RPM	FUEL (RAIL) PRESSURE (PSI)	% POWER (NORMALIZED TO MAXIMUM HORSEPOWER AT EACH RPM)	% FUEL PRES (NORMALIZED TO MAXIMUM FUEL PRES.)	% FUEL PRES (NORMALIZED TO MAXIMUM FUEL PRES. AT EACH RPM)
8	1400.	74.0	100.0	39.6	100.0
8	1400.	51.0	83.3	27.3	68.9
8	1400.	26.0	55.6	13.9	35.1
8	1400.	21.0	41.7	11.2	28.4
8	1800.	119.0	100.0	63.6	100.0
8	1800.	81.0	85.1	43.3	68.1
8	1800.	51.0	63.8	27.3	42.9
8	1800.	30.0	42.6	16.0	25.2
8	2200.	157.0	100.0	84.0	100.0
8	2200.	128.0	91.6	68.4	81.5
8	2200.	85.0	73.3	45.5	54.1
8	2200.	56.0	54.9	29.9	35.7
8	2600.	187.0	100.0	100.0	100.0
8	2600.	136.0	85.3	72.9	72.7
8	2600.	94.0	68.3	50.3	50.3
8	2600.	63.0	51.2	33.7	33.7



(Data supplied by Cummins Engine Co.)

FIGURE 1

normalized to maximum horsepower at each rpm was considered the dependent variable. Various powers of RPM and percent fuel pressure (normalized to maximum fuel pressure) were input to the regression analysis. In addition, interaction terms involving rpm and percent rail pressure were also entered. Table 3 summarizes the regression coefficients for the regression on each set of data.

The next step, in the data analysis, was to quantify the regression equations' estimation accuracies. Table 4 shows various parameters useful in comparing the regression equations' capabilities to predict % engine power, such as variance, multiple correlation coefficient, and standard error of the estimate. As can be seen from Table 4, the regression equation developed for each engine, provides a good estimation for % engine power. Assuming a normal distribution, 95% of the data will fall within $\pm$ 3% of the predicted values for the NTC-250, to $\pm$ 9% for the NTC-230 of the predicted values. Combining all of the engine data and performing a multiple stepwise regression, produces, at best, a fair prediction of the actual data (95% of the data will fall within $\pm$ 10% of the predicted values).

It was evident from the above analysis that one analytical expression would not be sufficient in predicting % engine power for all the turbocharged six cylinder Cummins engines in the CAPE-21 survey. Therefore, another approach was attempted in trying to develop a % HP model. Fuel pressure was normalized in a similar manner as horsepower. That is, fuel pressure was normalized to the maximum fuel pressure at each rpm.

Again, multiple, stepwise regressions were performed on each set of engine data and on all of the data combined. As before, % engine power was considered the dependent variable. Table 5 summarizes the regression coefficients for each set of data. Table 6, like Table 4. summarizes the variances, standard error of the estimates, and the multiple correlation coefficients for the regression analyses. All of the regression equations exhibit very good predictions of % HP. The NTC-290, NTC-335, NTC-350, NTC-230, and NTC-250 regression equations have multiple correlation coefficients greater than .998 and standard error of the estimates less than 1.412, thus indicating excellent % HP estimation.

Combining all of the engine data and performing a regression analysis, produces very good results. A multiple correlation of .997 and a standard error of the estimate of 1.651 were attained. These results suggest that the use of one analytical expression for the NTC engines would be justified. Furthermore, the analysis indicates that fuel pressure should be normalized to the maximum fuel pressure at each rpm.

The following discussion summarizes the analysis performed in further developing and refining a horsepower model for the NTC engines.

TABLE 3

Engine(s)	REGRESSION COEFFICIENTS — INDEPENDENT VARIABLES											Constant
	$(\%FP)^{.2}$	$(\%FP)^{.3}$	$(\%FP)^{.6}$	$(\%FP)$	$RPM^{.2}$	$RPM^{.25}$	$RPM^{.4}$	RPM^{3}	$RPM^{3.5}$	$(RPM \times \%FP)^{.25}$	$(RPM \times \%FP)^{.85}$	
NTC-290		50.3			-96.5				$.316 \times 10^{-10}$			333
NTC-335	129.5			.350	-163.5			$.569 \times 10^{-8}$		22.5	$.182 \times 10^{-2}$	500
NTC-350	195.3	-40.8			-2871	1545						2575
NTC-230		50.9			-58.2							169
NTC-250	110.1				$-.153 \times 10^{6}$	$.112 \times 10^{6}$	-5689					68193
All Engines NTC-290 NTC-335 NTC-350 NTC-230 NTC-250 (Data combined)			4.84		-152.1					17.8		500

NOTE: Fuel pressure is normalized to the maximum value.

TABLE 4

Data	Variance of Estimate	Standard Error of Estimate	Multiple Correlation Coefficient
NTC-290	4.2675	2.0658	.99599
NTC-335	3.4674	1.8621	.99602
NTC-350	8.7409	2.9565	.99199
NTC-230	20.0543	4.4782	.98336
NTC-250	1.9391	1.3925	.99820
All Engines NTC-290 NTC-335 NTC-350 NTC-230 NTC-250 (Data Combined)	23.7920	4.8777	.97483

TABLE 5

Engine(s)	REGRESSION COEFFICIENTS — INDEPENDENT VARIABLES								
	$(\%FP)^{.25}$	$(\%FP)^{.35}$	$(\%FP)^{.45}$	$(\%FP)^{.55}$	$RPM^{.6}$	RPM	RPM^3	$(RPM \times \% FP)^{.5}$	Constant
NTC-290		21.6			-.489			.105	- 8.71
NTC-335		32.4							-62.3
NTC-350	51.8					$-.900 \times 10^{-2}$		$.660 \times 10^{-1}$	-75.0
NTC-230				6.02	-.487			.116	18.7
NTC-250			11.9			$-.122 \times 10^{-1}$		$.918 \times 10^{-1}$	-11.0
All Engines NTC-290 NTC-335 NTC-350 NTC-230 NTC-250 (Data Combined)			17.1				$-.350 \times 10^{-9}$		-33.0

NOTE: Fuel pressure is normalized to the maximum value at each rpm.

TABLE 6

Data	Variance of Estimate	Standard Error of Estimate	Multiple Correlation Coefficient
NTC-290	1.9932	1.4118	.99813
NTC-335	1.3349	1.1554	.99821
NTC-350	1.3124	1.1456	.99876
NTC-230	.4243	.65136	.99966
NTC-250	.3358	.57948	.99968
All Engines NTC-290 NTC-335 NTC-350 NTC-230 NTC-250 (Data Combined)	2.7242	1.6505	.99713

The analysis discussed above was performed solely on Cummins supplied engine data. In general, the data points were reasonably spread over the operational range of the engine. However, no-load fuel pressures were not available. In fact, 40% power was the lowest power for which rail pressure data was available (see Table 2). From initial analyses of the CAPE-21 survey data, it was discovered that a substantial portion of the truck's operation was in the no-load/low-load area of the power curve. It would, therefore, be desirable to input no-load fuel pressure data into the regression analyses. A regression equation created from the Cummins engine data with additional no-load fuel pressure data would be a more accurate and better prediction for % horsepower. No-load rail pressures were calculated from the following equation:

$$\text{(Eq. A.)} \quad \text{Rail Pressure} = .1425 \times 10^{-6}\ \text{RPM}^{2.38} + 2.9419.$$

This equation was derived in a previous data analysis. The derivation and justification for its use for all Cummins six cylinder diesel engines are summarized in Appendix 1. Table 7 lists the Cummins engine data from Table 2 and the no-load fuel pressure data obtained from the equation above.

Using the data in Table 7, another multiple, stepwise regression was performed with percent engine horsepower as the dependent variable. Table 8 shows the coefficients resulting from the regression analyses, and Table 9 shows the variance, standard error of the estimates, and the multiple correlation coefficients for each regression equation. As in the previous analyses, the multiple correlation coefficients and standard error of the estimates for each set of engine data were very good, although not as good as the regression analyses performed only on the Cummins data. The introduction of no-load fuel pressures into the data appears to somewhat reduce the regression equations prediction accuracy.

The regression equation derived from the analysis on all of the engine data combined had a multiple correlation coefficient of .996 and a standard error of estimate of 2.867. Both figures indicate that the regression equation possesses sufficient prediction accuracy for application as a % horsepower model for the Cummins Diesel engines in the CAPE-21 survey. Thus, the justification for the use of one equation in modeling % HP for Cummins six cylinder Diesel is further fortified.

Table 10 compares the regression equations derived for all of the engine data combined. Equation 1 was derived from only Cummins supplied data, and Equation 2 was derived from Cummins data and no-load fuel pressure (predicted from equation A). Also appearing in Table 10 are various parameters to compare the regression equations' abilities to predict % engine horsepower. As can be seen from Table 10, both regression equations have similar variables. The regression equation

NTC-290

TABLE 7

CODE	ENGINE RPM	FUEL (RAIL) PRESSURE (PSI)	% POWER (NORMALIZED TO MAXIMUM HORSEPOWER AT EACH RPM)	% FUEL PRES (NORMALIZED TO MAXIMUM FUEL PRES.)	% FUEL PRES (NORMALIZED TO MAXIMUM FUEL PRES. AT EACH RPM)
1	1200.	81.0	100.0	50.0	100.0
1	1200.	63.0	89.3	38.9	77.8
1	1200.	50.0	79.8	30.9	61.7
1	1200.	32.0	60.1	19.8	39.5
1	1200.	20.0	39.9	12.3	24.7
1	1200.	6.0	0.0	3.7	7.4
1	1500.	108.0	100.0	66.7	100.0
1	1500.	89.0	89.8	54.9	82.4
1	1500.	74.0	79.1	45.7	68.5
1	1500.	49.0	59.9	30.2	45.4
1	1500.	30.0	40.1	18.5	27.8
1	1500.	8.1	0.0	5.0	7.5
1	1800.	145.0	100.0	89.5	100.0
1	1800.	120.0	90.2	74.1	82.8
1	1800.	97.0	79.9	59.9	66.9
1	1800.	65.0	59.8	40.1	44.8
1	1800.	38.0	40.2	23.5	26.2
1	1800.	10.9	0.0	6.7	7.5
1	1950.	144.0	100.0	88.9	100.0
1	1950.	120.0	89.9	74.1	83.3
1	1950.	96.0	78.6	59.3	66.7
1	1950.	65.0	59.7	40.1	45.1
1	1950.	40.0	40.3	24.7	27.8
1	1950.	12.6	0.0	7.8	8.7
1	2100.	162.0	100.0	100.0	100.0
1	2100.	137.0	90.2	84.6	84.6
1	2100.	115.0	79.7	71.0	71.0
1	2100.	80.0	60.1	49.4	49.4
1	2100.	48.0	39.9	29.6	29.6
1	2100.	14.4	0.0	8.9	8.9
1	2300.	162.0	100.0	100.0	100.0
1	2300.	136.0	89.0	84.0	84.0
1	2300.	118.0	79.4	72.8	72.8
1	2300.	80.0	59.6	49.4	49.4
1	2300.	50.0	39.7	30.9	30.9
1	2300.	17.2	0.0	10.6	10.6

NO-LOAD FUEL PRESSURES

PREDICTED BY:

$$FP = .1425 \times 10^{-6} \quad RPM^{2.38} + 2.9419$$

NTC-335

TABLE 7

CODE	ENGINE RPM	FUEL (RAIL) PRESSURE (PSI)	% POWER (NORMALIZED TO MAXIMUM HORSEPOWER AT EACH RPM)	% FUEL PRES (NORMALIZED TO MAXIMUM FUEL PRES.)	% FUEL PRES (NORMALIZED TO MAXIMUM FUEL PRES. AT EACH RPM)
2	1000.	46.0	100.0	23.7	100.0
2	1000.	35.0	85.7	18.0	76.1
2	1000.	26.0	71.4	13.4	56.5
2	1000.	19.0	57.1	9.8	41.3
2	1000.	14.0	42.9	7.2	30.4
2	1000.	4.9	0.0	3.0	9.3
2	1200.	73.0	100.0	37.6	100.0
2	1200.	56.0	86.3	28.9	76.7
2	1200.	41.0	71.7	21.1	56.2
2	1200.	30.0	58.3	15.5	41.1
2	1200.	22.0	45.0	11.3	30.1
2	1200.	6.0	0.0	3.7	6.4
2	1500.	124.0	100.0	63.9	100.0
2	1500.	95.0	86.5	49.0	76.6
2	1500.	73.0	73.0	37.6	58.9
2	1500.	55.0	59.6	28.4	44.4
2	1500.	39.0	46.2	20.1	31.5
2	1500.	8.1	0.0	5.0	4.1
2	1800.	166.0	100.0	85.6	100.0
2	1800.	129.0	87.3	66.5	77.7
2	1800.	105.0	74.8	54.1	63.3
2	1800.	80.0	62.4	41.2	48.2
2	1800.	58.0	49.9	29.9	34.9
2	1800.	10.9	0.0	6.7	3.9
2	1950.	183.0	100.0	94.3	100.0
2	1950.	149.0	88.1	76.8	81.4
2	1950.	118.0	75.7	60.8	64.5
2	1950.	88.0	63.3	45.4	48.1
2	1950.	61.0	50.8	31.4	33.3
2	1950.	12.6	0.0	7.8	4.0
2	2100.	194.0	100.0	100.0	100.0
2	2100.	158.0	87.7	81.4	81.4
2	2100.	126.0	75.2	64.9	64.9
2	2100.	97.0	62.6	50.0	50.0
2	2100.	71.0	50.1	36.6	36.6
2	2100.	14.4	0.0	8.9	4.1
2	2300.	17.2	0.0	10.6	5.6

TABLE 7

NTC-350

CODE	ENGINE RPM	FUEL (RAIL) PRESSURE (PSI)	% POWER (NORMALIZED TO MAXIMUM HORSEPOWER AT EACH RPM)	% FUEL PRES (NORMALIZED TO MAXIMUM FUEL PRES.)	% FUEL PRES (NORMALIZED TO MAXIMUM FUEL PRES. AT EACH RPM)
3	1100.	60.0	100.0	31.6	100.0
3	1100.	48.0	90.4	25.3	80.0
3	1100.	40.0	80.1	21.1	66.7
3	1100.	25.0	60.2	13.2	41.7
3	1100.	14.0	38.0	7.4	23.3
3	1100.	5.4	0.0	3.3	9.0
3	1300.	102.0	100.0	53.7	100.0
3	1300.	82.0	90.1	43.2	80.4
3	1300.	64.0	80.2	33.7	62.7
3	1300.	41.0	60.4	21.6	40.2
3	1300.	24.0	40.6	12.6	23.5
3	1300.	6.6	0.0	4.1	6.5
3	1500.	127.0	100.0	66.8	100.0
3	1500.	106.0	90.6	55.8	83.5
3	1500.	87.0	80.2	45.8	68.5
3	1500.	53.0	60.4	27.9	41.7
3	1500.	32.0	40.1	16.8	25.2
3	1500.	8.1	0.0	5.0	6.4
3	1800.	140.0	100.0	73.7	100.0
3	1800.	115.0	89.8	60.5	82.1
3	1800.	90.0	80.6	47.4	64.3
3	1800.	62.0	60.2	32.6	44.3
3	1800.	39.0	39.8	20.5	27.9
3	1800.	10.9	0.0	6.7	7.8
3	1950.	165.0	100.0	86.8	100.0
3	1950.	137.0	90.4	72.1	83.0
3	1950.	113.0	80.7	59.5	68.5
3	1950.	72.0	59.9	37.9	43.6
3	1950.	44.0	39.6	23.2	26.7
3	1950.	12.6	0.0	7.8	7.6
3	2100.	187.0	100.0	98.4	100.0
3	2100.	148.0	88.1	77.9	79.1
3	2100.	126.0	78.8	66.3	67.4
3	2100.	81.0	58.0	42.6	43.3
3	2100.	49.0	39.4	25.8	26.2
3	2100.	14.4	0.0	8.9	7.7
3	2300.	190.0	100.0	100.0	100.0
3	2300.	158.0	90.0	83.2	83.2
3	2300.	134.0	80.0	70.5	70.5
3	2300.	85.0	60.0	44.7	44.7
3	2300.	53.0	40.0	27.9	27.9
3	2300.	17.2	0.0	10.6	9.1

TABLE 7

NTC-230

CODE	ENGINE RPM	FUEL (RAIL) PRESSURE (PSI)	% POWER (NORMALIZED TO MAXIMUM HORSEPOWER AT EACH RPM)	% FUEL PRES (NORMALIZED TO MAXIMUM FUEL PRES.)	% FUEL PRES (NORMALIZED TO MAXIMUM FUEL PRES. AT EACH RPM)
4	1100.	76.0	100.0	48.4	100.0
4	1100.	68.0	94.6	43.3	89.5
4	1100.	46.0	75.0	29.3	60.5
4	1100.	26.0	50.0	16.6	34.2
4	1100.	19.0	39.9	12.1	25.0
4	1100.	5.4	0.0	3.3	7.1
4	1300.	99.0	100.0	63.1	100.0
4	1300.	67.0	79.0	42.7	67.7
4	1300.	37.0	52.7	23.6	37.4
4	1300.	27.0	42.0	17.2	27.3
4	1300.	6.6	0.0	4.1	6.7
4	1500.	90.0	100.0	57.3	100.0
4	1500.	83.0	95.0	52.9	92.2
4	1500.	58.0	75.0	36.9	64.4
4	1500.	33.0	50.0	21.0	36.7
4	1500.	25.0	40.0	15.9	27.8
4	1500.	8.1	0.0	5.0	9.0
4	1600.	135.0	100.0	86.0	100.0
4	1600.	124.0	94.9	79.0	91.9
4	1600.	85.0	75.0	54.1	63.0
4	1600.	48.0	50.0	30.6	35.6
4	1600.	36.0	39.8	22.9	26.7
4	1600.	9.0	0.0	5.5	6.6
4	1800.	131.0	100.0	83.4	100.0
4	1800.	124.0	96.4	79.0	94.7
4	1800.	87.0	75.8	55.4	66.4
4	1800.	50.0	50.8	31.8	38.2
4	1800.	38.0	40.3	24.2	29.0
4	1800.	10.9	0.0	6.7	8.3
4	1900.	134.0	100.0	85.4	100.0
4	1900.	124.0	95.2	79.0	92.5
4	1900.	89.0	75.2	56.7	66.4
4	1900.	54.0	50.0	34.4	40.3
4	1900.	40.0	40.4	25.5	29.9
4	1900.	12.0	0.0	7.4	9.0
4	2100.	139.0	100.0	88.5	100.0
4	2100.	129.0	95.1	82.2	92.8
4	2100.	94.0	75.5	59.9	67.6
4	2100.	56.0	50.6	35.7	40.3
4	2100.	44.0	40.4	28.0	31.7
4	2100.	14.4	0.0	8.9	10.4
4	2300.	157.0	100.0	100.0	100.0
4	2300.	147.0	95.3	93.6	93.6
4	2300.	107.0	75.3	68.2	68.2
4	2300.	64.0	50.2	40.8	40.8
4	2300.	50.0	40.0	31.8	31.8
4	2300.	17.2	0.0	10.6	11.0

TABLE 7

NTC-250

CODE	ENGINE RPM	FUEL (RAIL) PRESSURE (PSI)	% POWER (NORMALIZED TO MAXIMUM HORSEPOWER AT EACH RPM)	% FUEL PRES (NORMALIZED TO MAXIMUM FUEL PRES.)	% FUEL PRES (NORMALIZED TO MAXIMUM FUEL PRES. AT EACH RPM)
5	1200.	82.0	100.0	46.6	100.0
5	1200.	66.0	89.7	37.5	80.5
5	1200.	55.0	79.9	31.3	67.1
5	1200.	35.0	59.8	19.9	42.7
5	1200.	21.0	40.2	11.9	25.6
5	1200.	6.0	0.0	3.7	7.3
5	1400.	113.0	100.0	64.2	100.0
5	1400.	91.0	89.1	51.7	80.5
5	1400.	74.0	78.7	42.0	65.5
5	1400.	48.0	58.8	27.3	42.5
5	1400.	28.0	39.8	15.9	24.8
5	1400.	7.3	0.0	4.5	6.5
5	1500.	127.0	100.0	72.2	100.0
5	1500.	106.0	90.0	60.2	83.5
5	1500.	86.0	79.6	48.9	67.7
5	1500.	56.0	60.0	31.8	44.1
5	1500.	32.0	40.0	18.2	25.2
5	1500.	8.1	0.0	5.0	6.4
5	1800.	141.0	100.0	80.1	100.0
5	1800.	118.0	89.9	67.0	83.7
5	1800.	98.0	79.8	55.7	69.5
5	1800.	64.0	59.9	36.4	45.4
5	1800.	38.0	40.1	21.6	27.0
5	1800.	10.9	0.0	6.7	7.7
5	1950.	146.0	100.0	83.0	100.0
5	1950.	123.0	90.0	69.9	84.2
5	1950.	104.0	80.0	59.1	71.2
5	1950.	68.0	60.0	38.6	46.6
5	1950.	42.0	40.0	23.9	28.8
5	1950.	12.6	0.0	7.8	8.6
5	2100.	161.0	100.0	91.5	100.0
5	2100.	137.0	90.0	77.8	85.1
5	2100.	114.0	80.0	64.8	70.8
5	2100.	77.0	60.0	43.8	47.8
5	2100.	47.0	40.0	26.7	29.2
5	2100.	14.4	0.0	8.9	9.0
5	2300.	176.0	100.0	100.0	100.0
5	2300.	148.0	89.5	84.1	84.1
5	2300.	127.0	80.1	72.2	72.2
5	2300.	86.0	60.1	48.9	48.9
5	2300.	52.0	39.9	29.5	29.5
5	2300.	17.2	0.0	10.6	9.8

TABLE 8

Engine(s)	REGRESSION COEFFICIENTS									
	$(\%FP)^{.25}$	$(\%FP)^{.35}$	$(\%FP)^{.45}$	$RPM^{.2}$	RPM^{3}	$RPM^{3.5}$	$(RPM \times \%FP)^{.25}$	$(RPM \times \%FP)^{.5}$	$(RPM \times \%FP)$	Constant
NTC-290	62.4				$-.903 \times 10^{-9}$				$.531 \times 10^{-4}$	-100.5
NTC-335		51.1	17.1							- 35.0
NTC-350	66.7					$-.647 \times 10^{-11}$				-109.0
NTC-230		25.8		$RPM^{-.123 \times 10^{-1}}$				$.832 \times 10^{-1}$		- 42.2
NTC-250		25.3			$-.112 \times 10^{-8}$	$.182 \times 10^{-9}$	2.568			- 72.4
All Engines NTC-290 NTC-335 NTC-350 NTC-230 NTC-250 (Data Combined)		33.2				$-.775 \times 10^{-11}$				- 64.0

NOTE: Fuel pressure is normalized to the maximum value at each rpm.

TABLE 9

Data	Variance of Estimate	Standard Error of Estimate	Multiple Correlation Coefficient
NTC-290	2.3323	1.5272	.99909
NTC-335	6.8163	2.6108	.99711
NTC-350	3.3610	1.8333	.99864
NTC-230	2.4709	1.5719	.99905
NTC-250	1.8816	1.3717	.99926
All Engines NTC-290 NTC-335 NTC-350 NTC-230 NTC-250 (Data Combined)	8.2219	2.8674	.99648

TABLE 10

Regression Analyses Summary for All Engine Data Combined (NTC-290, NTC-335, NTC-350, NTC-230, & NTC-250)

Eq. No.	Input Data	REGRESSION COEFFICIENTS					Variance of Estimate	Std. Error of Estimate	Multiple Correlation Coefficient	Range of Residuals	Range of Residuals / Std. Error of Estimate
		$(\%FP)^{.35}$	$(\%FP)^{.45}$	RPM^3	$RPM^{3.5}$	Constant					
1	Cummins Data		17.1	$-.350 \times 10^{-9}$	$.775 \times 10^{-11}$	-33.0	2.7240	1.6505	.9971	-4.61 to 4.57	5.558
2	Cummins Data and No-Load Fuel Pressure Data	33.2				-64.0	8.2219	2.8674	.9965	-8.19 to 13.00	7.388

NOTE: Fuel pressure is normalized to the maximum value at each rpm.

developed from the Cummins data gives a somewhat better prediction of % power than the regression equation developed from the Cummins data with no-load fuel pressures. Specifically, the standard error of the estimates are 1.6505 for Equation 1 and 2.8674 for Equation 2. The multiple correlation coefficient for Equation 1 was marginally better than Equation 2, .9971 and .9965 respectively. Both equations have acceptable prediction accuracy for % power. However, since Equation 2 (regression equation derived from Cummins engine data and no-load fuel pressure data) was derived from a more representative and extensive data base, its use is recommended.

The distribution about the means of percent power for the regression equation based on the Cummins data and the no-load fuel pressures were assumed normal. Thus, for Equation 2, 95% of the data will fall within $\pm$ 5.62% ($\pm$ 1.96 x 2.8674) of the predicted values for % engine horsepower (or 68% of the data will fall within $\pm$ 2.87% of the predicted values for % engine horsepower).

2. Small V-8 Diesel Engines (Naturally Aspirated)

Multiple, stepwise regressions were performed on the small V-8 engine data, in a similar fashion as performed on the NTC data. Percent engine power (normalized to maximum horsepower at each rpm) was considered the dependent variable. Percent engine power was assumed to be a function of rpm and percent fuel pressure (normalized to maximum value of fuel pressure). Table 11 summarizes the resulting regression coefficients and regression equation descriptive parameters for the V8-210 and V-555. The regression equations all had very good estimation ability, although, when the data for both engines were combined, the prediction for percent power was slightly worse. In particular, the standard error for the V8-210, V-555, and both engines combined are .874, 1.957, and 2.665 respectively.

As was done in the NTC analysis, fuel pressure was then normalized to the maximum fuel pressure at each rpm. Multiple, stepwise regressions were repeated. Table 12 similarly lists the resulting regression coefficients and regression equation descriptive parameters. Again, all three regressions produced excellent prediction equations. Both sets of regressions (Tables 11 and 12) produce prediction equations of comparable accuracy. However, when fuel pressure is normalized to the maximum fuel pressure at each rpm, the resulting regression equation has fewer independent variables. Thus, a simpler, yet as accurate % power prediction is effected.

TABLE 11

Engine's	REGRESSION COEFFICIENTS — INDEPENDENT VARIABLES									Variance of Estimate	Standard Error of Estimate	Multiple Correlation Coefficient
	$\%FP^{.2}$	$\%FP^{.3}$	%FP	RPM	$RPM^{.4}$	$RPM^{3.5}$	$(\%FP \times RPM)^{.75}$	$(\%FP \times RPM)^{.25}$	Constant			
V8-210 (V-504)	140.7		-1.122	-74.1		$-.462 \times 10^{-11}$	$.691 \times 10^{-2}$		146.6	.7636	.87382	.99689
V-555		133.0			-.118			-16.42	-30.7	3.8310	1.9573	.99800
Both Engines												
V8-210					-6.50							
V-555	99.0								18.03	7.1017	2.6649	.99561
(Data Combined)												

NOTE: Fuel pressure normalized to the maximum value.

TABLE 12

Engine's	REGRESSION COEFFICIENTS — INDEPENDENT VARIABLES					Variance of Estimate	Standard Error of Estimate	Multiple Correlation Coefficient
	$\%FP^{.15}$	$\%FP^{.25}$	%FP	$RPM^{3.5}$	Constant			
V8-210 (V-504)	139.2			$-.1119 \times 10^{-11}$	-175.8	1.1306	1.0633	.99491
V-555			31.79		- 58.0	4.4306	2.1049	.99761
Both Engines V8-210 V -555 (Data Combined)		64.1			-101.1	8.8292	2.9714	.99448

NOTE: Fuel pressure normalized to the maximum value at each rpm.

3. Medium V-8 Diesel Engines (Naturally Aspirated)

As done in the NTC and small V-8 data analyses, multiple stepwise regressions were performed with percent engine power as the dependent variable. In the first regression, % power was assumed to be a function of rpm and percent fuel pressure (normalized to maximum value of fuel pressure). The following equation was obtained from the regression:

$$\text{(Eq. B) \% POWER} = -99.358\ (\%FP)^{.3} + 321.08\ (\%FP)^{.2} + .19462 \times 10^{-9}\ (RPM)^{3.2} - 98.289\ RPM^{.2} + 145.22$$

The multiple correlation coefficient is .999 and the standard error of the estimate is 1.312 for this equation.

Another multiple, stepwise regression was repeated, but fuel pressure was now normalized to maximum fuel pressure at each rpm. The resulting equation was:

$$\text{(Eq. C) \% POWER} = 160.33\ (\%FP)^{.15} - 219.30$$

The multiple correlation coefficient and standard error of the estimate for this equation are .998 and 1.536, respectively.

Like the small V-8 regressions, both regressions above produce % power prediction equations with comparable accuracy. The latter regression however, is in a much simpler form (since the prediction is independent of RPM), and would be favored as a % power model for medium V-8 diesel engines.

C. Combined Analysis

It is evident from all three analyses, that when fuel pressures are normalized to the maximum fuel pressure at each rpm, a more accurate % power prediction can be attained. This is true especially for the NTC % power equation. Also, a shorter and simpler prediction is always derived. Thus, the decision was made to use only the results obtained from the analyses performed when fuel pressure was normalized to the maximum value at each rpm, in deciding upon a method or methods of characterizing % engine power. All fuel pressures appearing in the following discussion, are fuel pressures normalized to the maximum fuel pressure at each rpm.

Based on the analyses performed several approaches can be taken in modeling engine HP for the engines (trucks) in the CAPE-21 survey. The following are summaries of two possible approach to modeling engine HP for Cummins Diesel engines.

The first approach would be to use the regression equations as derived for each set of engine data. The following equation would be used for in-line, six cylinder Diesel engines (turbocharged):

$$\text{(Eq. D) \% POWER} = 33.2\ (\%FP)^{.35} - .775 \times 10^{-11}\ RPM^{3.5} - 64.0$$
$$R = .9965,\ SE = 2.8674$$

Also as discussed before, the following equation could be used to predict % engine HP for the small V-8 Diesel engines (naturally aspirated):

$$\text{(Eq. E) \% POWER} = 64.1\ (\%FP)^{.25} - 101.1$$
$$R = .9945,\ SE = 2.9714$$

Finally the following equation would be used for the medium V-8's (V-903):

$$\text{(Eq. F) \% POWER} = 160.33\ (\%FP)^{.15} - 219.30$$
$$R = .998,\ SE = 1.536$$

All three equations have sufficient prediction accuracy for % engine power for the in-line six cylinder (turbocharged) engines and the naturally aspirated small and medium V-8's. However, these engines constitute only 42% of the surveyed engines. Thus 58% still need a model for % HP prediction. Naturally aspirated in-line six cylinder engines comprise the remaining engines. In order to characterize the % power for these engines, engine data for the naturally aspirated in-line six cylinder diesel engine must be analyzed. Perhaps the turbocharged in-line six % power model will also be valid for the naturally aspirated in-line six diesel engines. Without analyzing actual data, there is nothing suggesting that the % model will be the same.

Another approach in modeling % engine power, would be to eliminate rpm as a variable. When rpm is considered as an independent variable, the data treatment and subsequent percent power models (for the in-line sixes, small V-8's, and medium V-8's) must be different. However, by eliminating rpm as an independent variable, the data for the three engines can then be combined and analyzed. This opens up the possibility of reducing the number of % power models, hopefully to one. In using this approach, % power was assumed to be only a function of percent fuel pressure (normalized to the maximum value at each rpm). This assumption seemed reasonable, since in all the regression analyses some power of fuel pressure was always the first term selected, and also, it contributed most to the correlation of the regression equation. Initially, a regression analysis was performed on all of the engine data: NTC engine data with no-load fuel pressures, small V-8 engine data, and medium V-8 data. In particular, it was found that percent power was proportional to $\%FP^{.33}$. The resulting regression equation was:

(Eq. G) % POWER = $37.475\ (\%FP)^{.33} - 70.283$

Figure 2 shows the plot of the above equation.

The multiple correlation coefficient was .9935 and the standard error of the estimate 3.6370. These values indicate that the above approach is quite valid. For CAPE-21 purposes, the estimation accuracy is more than adequate. The multiple correlation coefficient of .9935 is comparable to the coefficients of the individual engine % power models previously presented in the first approach. Although the standard error of the estimate is not as good as the % power models presented in the first approach, the accuracy is still comparable. In fact, by using the % power model above (equation G), any errors which may have been present in rpm measurement are not introduced into the % power values. The errors in rpm measurement cannot be quantified, but they surely exist. Also, the above % power model is simple, and results of the analyses indicate that the one equation is valid for turbocharged in-line six cylinder engines (NTC's), naturally aspirated small V-8 engines (V8-210 and V-555), and naturally aspirated medium V-8 engines (V-903). Although no naturally aspirated in-line six cylinder data has been included in the development of the % power model, it is expected that equation G will be equally applicable to the naturally aspirated in-line six cylinders. Naturally aspirated V-8 data was included in the analyses, and it is expected that naturally aspirated in-line six cylinder data is quite similar.

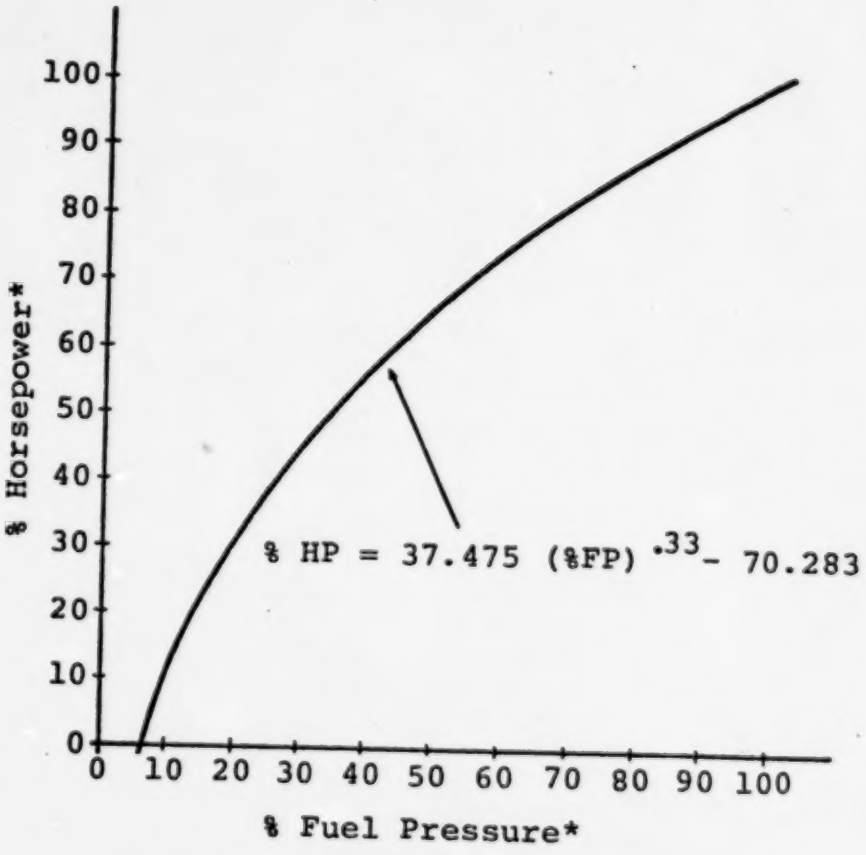
Two additional constraints will have to be applied simultaneously with either of the above approaches. They are:

1) When predicted % HP is less than 0%, then the power is identified as a motoring value and

2) When predicted % HP is greater than 100%, then % HP is changed to 100%.

When fuel pressure falls below the no-load value, the % HP models will produce negative % HP values. Although the numerical values obtained are probably meaningless, the negative sign most certainly denotes engine motoring. According to Cummins Engine Co., when their diesel engines are motored, the fuel supply is reduced to a minimum. During motoring the only purpose of the limited fuel supply is to lubricate the injectors. The fuel pressure during this condition will be less than the no-load fuel pressure.

CUMMINS DIESEL ENGINE
% HORSEPOWER MODEL



*Normalized to maximum value at each RPM

FIGURE 2

Consequently, when a fuel pressure less than a no-load fuel pressure is inputted into the % HP models, a negative % HP value will be obtained. The negative sign readily identifies a motoring condition. Either approach discussed earlier describes motoring adequately.

The second condition is required since none of the models are 100% accurate. Consequently, % HP values greater than 100% may be calculated. Of course, % HP values greater than 100% would be erroneous, therefore, they are set at 100%.

From an application viewpoint, either approach could be incorporated easily into the heavy-duty cycle development program. However, the fuel pressure values on the data tapes will have to be normalized to the maximum fuel pressure at each rpm. Consequently, the maximum fuel pressure versus rpm curve for each engine (truck) is required. This curve could be obtained in two possible ways. The first method would be to derive the curve from each truck's dynamometer calibration data. This data includes approximately five maximum fuel pressure points which should be sufficient to define the curve. Another approach would be to use the maximum fuel pressures (at different rpm values) observed on the tapes to define the maximum fuel pressure versus rpm curve. Of course, it is assumed that the observed maximum fuel pressures occur at 100% power. Perhaps, both approaches could be used together. Thus, means of verifying the curve would be possible.

D. Summary and Conclusions

In summarization, either of the two general approaches presented possess the necessary accuracy for application as a % power model in the CAPE-21 survey. The use of the second approach (equation G) is simpler, and is expected to be equally applicable to naturally aspirated in-line six cylinder engines. Since rpm is not a variable in the analytical expression an additional benefit is obtained in using equation G as a % power model. Errors involved in the rpm measurement during the data collection are not built into the model prediction for % power. To incorporate the % HP model into the heavy duty cycle development program, the fuel pressures on the tape will have to be normalized to the maximum fuel pressure at each rpm. A maximum fuel pressure versus rpm curve for each truck will be required to normalize fuel pressure in this manner. As discussed earlier, this could be obtained either from the truck calibration data or from the tape data.

IV. Detroit Diesel Engine Horsepower Model Development

A. Introduction

For Detroit Diesel engines surveyed in CAPE-21, rack position (travel) was recorded in an attempt to measure engine power output. In attempting to convert rack position to % HP an extensive data analysis had to be performed. Initially, engine data had to be collected. After this was done, the rack position versus % HP relationship could be ascertained, and subsequently an accurate analytical model determined. The following discussion summarizes the work conducted in arriving at such a model.

Listed in Table 13 are all of the DDA diesel engines that were surveyed during the conduction of CAPE-21. As illustrated by the list, a great majority of the DDA diesel engines were surveyed in the Los Angeles area. Also, fourteen of the twenty engines are 8V-71's. The remaining six engines are six cylinder models 6V-71N and 6V-53N. Of the fourteen 8V-71's, twelve were naturally aspirated. Los Angeles truck numbers 29 and 33 were both 8V-71 models with turbochargers.

An important characteristic influencing an individual engine's rack position versus power relationship is the injector type. Different injectors will produce varying amounts of power. Figures 3 demonstrates the relationship between rack travel and % theoretical output (theoretical output can be considered linear with % power) for five different injectors.

Realizing the importance of injector type on power output, Roy Higdon, CAPE-21 project officer, conducted a field inspection of all the DDA engines tested in Los Angeles. He determined that all of the Los Angeles DDA diesel engines were equipped with N-65 injectors.

The DDA diesel engines surveyed in New York City could not be inspected in the field. However, only seven of the total DDA engine samples were in the New York portion of the CAPE-21 survey. Also, for truck number 42 in New York, DDA expected that it most likely had N-65 injectors. This was determined from the engine serial number and the sales data for that engine. For the other six engines, the serial numbers were unavailable, therefore, the injector types are unknown.

Once identifying that the majority of DDA engines tested were 8V-71N with N-65 injectors, EPA approached DDA about borrowing an engine (8V-71N) for testing. DDA then proposed to collect the data for EPA at their testing facilities in Detroit, Michigan. Table 14 is a data listing of the data collected and supplied by DDA. Figure 4 shows a portion of the data graphically. As indicated in Table 2 rack travel was measured in inches. Also, since all DDA racks travel .780 + .030, -.000 inches, the rack travel in inches was normalized. The rack travel was converted to % travel by the following equation:

Table 13

Detroit Diesel Engines

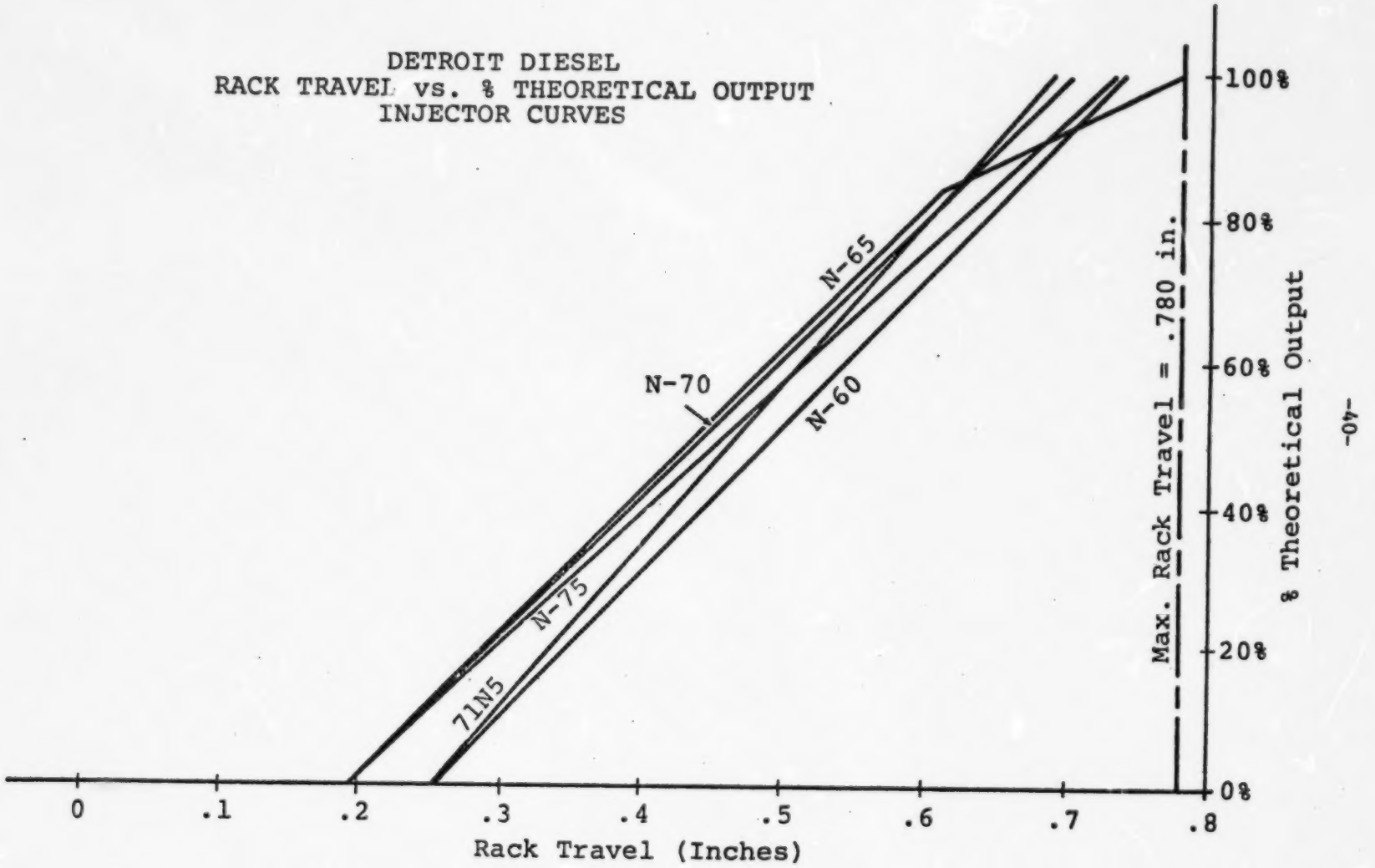
Los Angeles Survey

Truck No.	Engine	Injector Type
06	8V-71N (8 cyl)	N-65
15	8V-71N (8 cyl)	N-65
22	8V-71N (8 cyl)	N-65
23	8V-71N (8 cyl)	N-65
27	8V-71N (8 cyl)	N-65
51	8V-71N (8 cyl)	N-65
29	8V-71T (8 cyl)	N-65
33	8V-71T (8 cyl)	N-65
41	8V-71N (8 cyl)	N-65
45	8V-71N (8 cyl)	N-65
90	8V-71N (8 cyl)	N-65
91	8V-71N (8 cyl)	N-65
94	8V-71N (8 cyl)	N-65

New York City Survey

Truck No.	Engine	Injector Type
42	6V-71N (6 cyl)	N-65
55	8V-71N (8 cyl)	
56	6V-53N (6 cyl)	

Bus No.		
80	6V-71N (6cyl)	
81	6V-71N (6 cyl)	
82	6V-71N (6 cyl)	
83	6V-71N (6 cyl)	



(Data supplied by Detroit Diesel)

FIGURE 3

TABLE 14 (PAGE 1 OF 2)

(1- 92) : 8V-71N W/N-65 INJECTORS

CODE	ENGINE RPM	TORQUE (FT-LBS)	%POWER	RACK TRAVEL (MV)	RACK TRAVEL (IN.)	RACK TRAVEL (%)
1	795	194	30.0	644	2.21	57.7
1	798	322	50.0	684	2.15	50.0
1	800	129	20.0	627	2.24	61.6
1	800	580	90.0	774	2.00	30.8
1	800	258	40.0	664	2.18	53.9
1	801	516	80.0	747	2.04	35.9
1	801	64	10.0	606	2.28	66.7
1	804	645	100.0	921	1.76	0.0
1	804	452	70.0	724	2.08	41.0
1	807	387	60.0	704	2.11	44.9
2	999	476	70.0	735	2.06	38.5
2	1000	204	30.0	646	2.21	57.7
2	1000	543	80.0	758	2.02	33.3
2	1001	340	50.0	689	2.14	48.7
2	1001	272	40.0	664	2.18	53.9
2	1002	136	20.0	627	2.24	61.6
2	1002	408	60.0	713	2.10	43.6
2	1004	612	90.0	790	1.97	26.9
2	1005	68	10.0	602	2.28	66.7
2	1005	680	100.0	921	1.76	0.0
3	1198	72	10.0	603	2.28	66.7
3	1199	572	80.0	772	2.00	30.8
3	1199	429	60.0	722	2.08	41.0
3	1199	358	50.0	697	2.13	47.4
3	1200	501	70.0	745	2.05	37.2
3	1201	716	100.0	921	1.76	0.0
3	1201	286	40.0	673	2.17	52.6
3	1202	643	90.0	804	1.95	24.4
3	1203	143	20.0	630	2.24	61.6
3	1204	215	30.0	651	2.20	56.4
4	1398	148	20.0	630	2.24	61.6
4	1399	592	80.0	783	1.98	28.2
4	1399	222	30.0	657	2.19	55.1
4	1399	518	70.0	756	2.03	34.6
4	1400	444	60.0	728	2.07	39.7
4	1400	666	90.0	814	1.93	21.8
4	1401	74	10.0	605	2.28	66.7
4	1401	296	40.0	678	2.16	51.3
4	1402	740	100.0	921	1.76	0.0
4	1404	370	50.0	704	2.11	44.9
5	1597	517	70.0	772	2.00	30.8
5	1598	590	80.0	799	1.96	25.6
5	1600	295	40.0	695	2.13	47.4
5	1600	443	60.0	748	2.04	35.9
5	1600	369	50.0	721	2.09	42.3
5	1602	148	20.0	647	2.21	57.7

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TABLE 14 (PAGE 2 OF 2)

(1- 92) : AV-71N W/N-65 INJECTORS

CODE	ENGINE RPM	TORQUE (FT-LBS)	%POWER	RACK TRAVEL (MV)	(IN.)	(%)
5	1802	664	90.0	832	1.90	17.9
5	1802	221	30.0	671	2.17	52.6
5	1803	738	100.0	91[illegible]	1.76	0.0
5	1803	74	10.0	62[illegible]	2.25	62.8
6	1799	295	40.0	701	2.12	46.2
6	1799	74	10.0	626	2.24	61.6
6	1800	737	100.0	928	1.74	0.0
6	1800	221	30.0	676	2.16	51.3
6	1800	589	80.0	807	1.94	23.1
6	1800	147	20.0	651	2.20	56.4
6	1801	663	90.0	841	1.89	16.7
6	1801	442	60.0	75[illegible]	2.04	35.9
6	1801	369	50.0	725	2.08	41.0
6	1803	516	70.0	77[illegible]	1.99	29.5
7	1999	362	50.0	731	2.07	39.7
7	2000	651	90.0	851	1.87	14.1
7	2000	217	30.0	684	2.15	50.0
7	2001	434	60.0	757	2.03	34.6
7	2001	144	20.0	656	2.19	55.1
7	2002	579	80.0	81[illegible]	1.93	21.8
7	2002	289	40.0	707	2.11	44.9
7	2002	506	70.0	786	1.98	28.2
7	2003	723	100.0	922	1.75	0.0
7	2005	72	10.0	627	2.24	61.6
9	2198	413	60.0	75[illegible]	2.02	33.3
9	2199	344	50.0	73[illegible]	2.06	38.5
9	2200	275	40.0	712	2.10	43.6
9	2201	618	90.0	85[illegible]	1.87	14.1
9	2201	206	30.0	685	2.14	48.7
9	2201	482	70.0	787	1.98	28.2
9	2202	688	100.0	925	1.75	0.0
9	2202	550	80.0	814	1.93	21.8
9	2203	137	20.0	662	2.18	53.9
9	2205	69	10.0	633	2.23	60.3
10	2250	22	3.0	603	2.28	66.7
10	2250	586	100.0	911	1.77	1.3
10	2251	412	60.0	75[illegible]	2.04	35.9
10	2251	137	20.0	65[illegible]	2.20	56.4
10	2251	274	40.0	70[illegible]	2.12	46.2
10	2252	549	80.0	785	1.98	28.2
11	2298	138	20.0	652	2.20	56.4
11	2300	27	4.0	60[illegible]	2.27	65.4
11	2301	675	100.0	91[illegible]	1.77	1.3
11	2302	404	60.0	755	2.03	34.6
11	2302	268	40.0	704	2.11	44.9
11	2304	538	80.0	807	1.94	23.1

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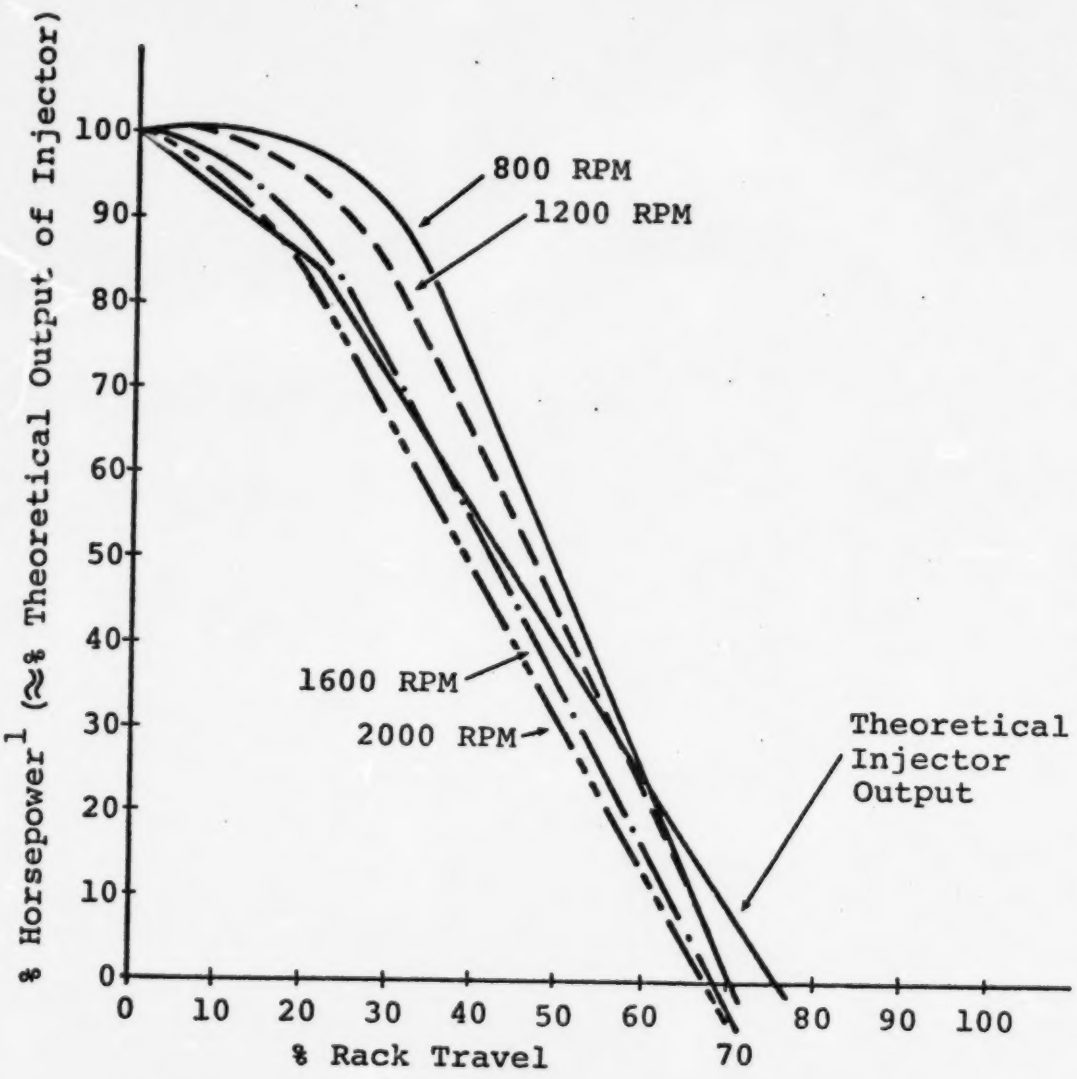
DDA DATA
8V-7IN W/N-65 INJECTORS
% RACK TRAVEL vs. % HORSEPOWER



[1]Normalized to maximum value at each RPM
[2]Normalized to maximum value

FIGURE 4

$$\% \text{ RACK TRAVEL} = \frac{\text{inches-minimum}}{.780}$$

B. Data Analysis

The first step in the data analysis was to run multiple stepwise regressions on the data in Table 14. Percent engine power (normalized to maximum horsepower at each rpm) was considered the dependent variable. For the regression analysis, % engine power was assumed a function of engine rpm and percent rack travel. Various powers of rpm and % rack travel were input to the regression analysis. Logs of rpm and rack travel were also input. In addition, interaction terms involving rpm and for % rack travel were included. The resulting regression equation was:

$$\text{(Eq. 1) \% POWER} = -22.303\ (\log_{10} \text{RPM}) - .44663 \times 10^{-1}\ (\% \text{ RACK}^{1.56})\ (\log_{10} \text{RPM}) + 173.16$$

The multiple correlation coefficient and the standard error of the estimate for this equation are .9923 and 3.7040, respectively.

The above regression equation appears to have adequate prediction capability for % horsepower for Detroit Diesel engines. However, it would be desirable to improve the equation's prediction accuracy if possible. The approach taken to improve the prediction was to add more input points to the regression analysis. This was done by interpolation. By interpolating, 36 more input data points were added. Table 15 is a data listing of the data in Table 14 plus the interpolated data points.

Again, another multiple stepwise regression was performed on the data. Percent engine power was considered the dependent variable. Various independent variables, as described earlier, were entered into the regression analysis. The following equation was obtained from the regression:

$$\text{(Eq. 2) \% POWER} = -22.507\ (\log_{10} \text{RPM}) - .44802 \times 10^{-1}\ (\% \text{ RACK}^{1.56})\ (\log_{10} \text{RPM}) + 173.90$$

The multiple correlation coefficient is .9933 and the standard error of the estimate is 3.6202 for this equation.

TABLE 15 (PAGE 1 OF 3)

(1-128) : 8V-71N W/N-65 INJECTORS

NOTE: * REPRESENTS AN INTERPOLATED POINT.

CODE	ENGINE RPM	TORQUE (FT-LBS)	%POWER	RACK TRAVEL (MV)	RACK TRAVEL (IN.)	RACK TRAVEL (%)	
1	795	194	30.0	644	2.21	57.7	
1	798	322	50.0	684	2.15	50.0	
1	800		94.3			25.3	*
1	800	129	20.0	627	2.24	61.6	
1	800		98.3			15.2	*
1	800	580	90.0	774	2.00	30.8	
1	800		99.8			5.1	*
1	800	258	40.0	664	2.18	53.9	
1	801	516	80.0	747	2.04	35.9	
1	801	64	10.0	606	2.28	66.7	
1	804	645	100.0	921	1.76	0.0	
1	804	452	70.0	724	2.08	41.0	
1	807	387	60.0	704	2.11	44.9	
2	999	476	70.0	735	2.06	38.5	
2	1000		93.5			22.8	*
2	1000	204	30.0	646	2.21	57.7	
2	1000		99.5			5.1	*
2	1000	543	80.0	758	2.02	33.3	
2	1000		97.3			15.2	*
2	1001	340	50.0	689	2.14	48.7	
2	1001	272	40.0	664	2.18	53.9	
2	1002	136	20.0	627	2.24	61.6	
2	1002	408	60.0	713	2.10	43.6	
2	1004	612	90.0	790	1.97	26.9	
2	1005	68	10.0	602	2.28	66.7	
2	1005	680	100.0	921	1.76	0.0	
3	1198	72	10.0	603	2.28	66.7	
3	1199	572	80.0	772	2.00	30.8	
3	1199	429	60.0	722	2.08	41.0	
3	1199	358	50.0	697	2.13	47.4	
3	1200		96.5			15.2	*
3	1200	501	70.0	745	2.05	37.2	
3	1200		94.0			20.3	*
3	1200		98.8			7.6	*
3	1201	716	100.0	921	1.76	0.0	
3	1201	286	40.0	673	2.17	52.6	
3	1202	643	90.0	804	1.95	24.4	
3	1203	143	20.0	630	2.24	61.6	
3	1204	215	30.0	651	2.20	56.4	
4	1398	148	20.0	630	2.24	61.6	
4	1399	592	80.0	783	1.98	28.2	
4	1399	222	30.0	657	2.19	55.1	
4	1399	518	70.0	756	2.03	34.6	

TABLE 15 (PAGE 2 OF 3)

(1-128) : 8V-71N W/N-65 INJECTORS

NOTE: * REPRESENTS AN INTERPOLATED POINT.

CODE	ENGINE RPM	TORQUE (FT-LBS)	%POWER	RACK TRAVEL (MV)	RACK TRAVEL (IN.)	RACK TRAVEL (%)	
4	1400		95.5			15.2	*
4	1400	444	60.0	728	2.07	39.7	
4	1400		99.0			5.1	*
4	1400	666	90.0	814	1.93	21.8	
4	1401	74	10.0	605	2.28	66.7	
4	1401	296	40.0	678	2.16	51.3	
4	1402	740	100.0	921	1.76	0.0	
4	1404	370	50.0	704	2.11	44.9	
5	1597	517	70.0	772	2.00	30.8	
5	1598	590	80.0	799	1.96	25.6	
5	1600		94.8			12.7	*
5	1600	295	40.0	695	2.13	47.4	
5	1600		98.5			5.1	*
5	1600	443	60.0	746	2.04	35.9	
5	1600	369	50.0	721	2.09	42.3	
5	1602	148	20.0	647	2.21	57.7	
5	1602	664	90.0	832	1.90	17.9	
5	1602	221	30.0	671	2.17	52.6	
5	1603	738	100.0	916	1.76	0.0	
5	1603	74	10.0	620	2.25	62.8	
6	1799	295	40.0	701	2.12	46.2	
6	1799	74	10.0	626	2.24	61.6	
6	1800		98.6			5.1	*
6	1800	737	100.0	928	1.74	0.0	
6	1800		85.6			20.3	*
6	1800	221	30.0	676	2.16	51.3	
6	1800		93.8			12.7	*
6	1800	589	80.0	807	1.94	23.1	
6	1800	147	20.0	651	2.20	56.4	
6	1801	663	90.0	841	1.89	16.7	
6	1801	442	60.0	750	2.04	35.9	
6	1801	369	50.0	725	2.08	41.0	
6	1803	516	70.0	779	1.99	29.5	
7	1999	362	50.0	731	2.07	39.7	
7	2000	651	90.0	851	1.87	14.1	
7	2000		97.5			5.1	*
7	2000	217	30.0	684	2.15	50.0	
7	2000		93.8			10.1	*
7	2001	434	60.0	757	2.03	34.6	
7	2001	144	20.0	656	2.19	55.1	
7	2002	578	80.0	815	1.93	21.8	
7	2002	289	40.0	707	2.11	44.9	
7	2002	506	70.0	786	1.98	28.2	

TABLE 15 (PAGE 3 OF 3)

(1-128) : 8V-71N W/N-65 INJECTORS

NOTE: * REPRESENTS AN INTERPOLATED POINT.

CODE	ENGINE RPM	TORQUE (FT-LBS)	%POWER	RACK TRAVEL (MV)	RACK TRAVEL (IN.)	RACK TRAVEL (%)	
7	2003	723	100.0	922	1.75	0.0	
7	2005	72	10.0	627	2.24	61.6	
8	2100		90.0			14.1	*
8	2100		100.0			0.0	*
8	2100		10.0			60.8	*
8	2100		50.0			39.0	*
8	2100		70.0			28.2	*
8	2100		30.0			49.2	*
8	2100		80.0			21.8	*
8	2100		40.0			44.3	*
8	2100		60.0			34.1	*
8	2100		20.0			54.4	*
9	2198	413	60.0	758	2.02	33.3	
9	2199	344	50.0	736	2.06	38.5	
9	2200		97.6			5.1	*
9	2200	275	40.0	712	2.10	43.6	
9	2200		94.1			10.1	*
9	2201	618	90.0	850	1.87	14.1	
9	2201	206	30.0	686	2.14	48.7	
9	2201	482	70.0	787	1.98	28.2	
9	2202	688	100.0	925	1.75	0.0	
9	2202	550	80.0	814	1.93	21.8	
9	2203	137	20.0	662	2.18	53.9	
9	2205	69	10.0	633	2.23	60.3	
10	2250		94.8			15.2	*
10	2250	22	3.0	603	2.28	66.7	
10	2250		86.8			22.8	*
10	2250	686	100.0	911	1.77	1.3	
10	2250		99.0			7.6	*
10	2251	412	60.0	750	2.04	35.9	
10	2251	137	20.0	650	2.20	56.4	
10	2251	274	40.0	700	2.12	46.2	
10	2252	549	80.0	785	1.98	28.2	
11	2298	138	20.0	652	2.20	56.4	
11	2300		83.1			20.0	*
11	2300	27	4.0	608	2.27	65.4	
11	2300		95.5			6.0	*
11	2300		89.3			12.9	*
11	2301	675	100.0	910	1.77	1.3	
11	2302	404	60.0	755	2.03	34.6	
11	2302	268	40.0	704	2.11	44.9	
11	2304	538	80.0	807	1.94	23.1	

The above equation (eq. 2) has somewhat better % power prediction than equation 1. Apparently, the addition of the interpolated data points results in the increased accuracy. Table 16 compares equations 1 and 2. Both regression coefficients and various descriptive parameters are summarized.

Table 16 illustrates that both regressions produce the same independent variables. In addition, the regression coefficients and equation constants are of the same order of magnitude. More importantly, equation 2 demonstrates a better % horsepower prediction. Thus, the addition of the interpolated data points improved the regression equation accuracy. The summary statistics in Table 16 demonstrate that equation 2 has sufficient % HP prediction accuracy for % engine power for the naturally aspirated DDA engines equipped with N-65 injectors.

C. Discussion

Through regression analyses, the following analytical expression was derived to predict % HP for the DDA engines (w/N-65 injectors):

$$\text{(Eq. 3)}\ \%\ \text{POWER} = -22.507\ (\log_{10}\ \text{RPM}) - .44802 \times 10^{-1}\ (\%\ \text{RACK}^{1.56})\ (\log_{10}\ \text{RPM}) + 173.90$$

In using this equation two constraints will have to be applied with its use. They are:

1. When predicted % HP is less than 0% then the % HP prediction is identified as motoring.

2. When predicted % HP is greater than 100%, then % HP is changed to 100%.

3. Maximum governed RPM was set at 2400.

These conditions are necessary since negative % powers and % powers in excess of 100% would be meaningless. Although negative % HP values can be identified as motoring, the degree of motoring as indicated by the negative value is not very meaningful. This is true, because when a DDA diesel engine is motored the rack positions itself in a no-fuel position. Of course this no-fuel rack position is always less than idle rack position. The second condition is required since the regression equation is not 100% accurate, therefore some % HP values will be predicted with values greater than 100%. Needless to say, these values would be erroneous.

Table 16

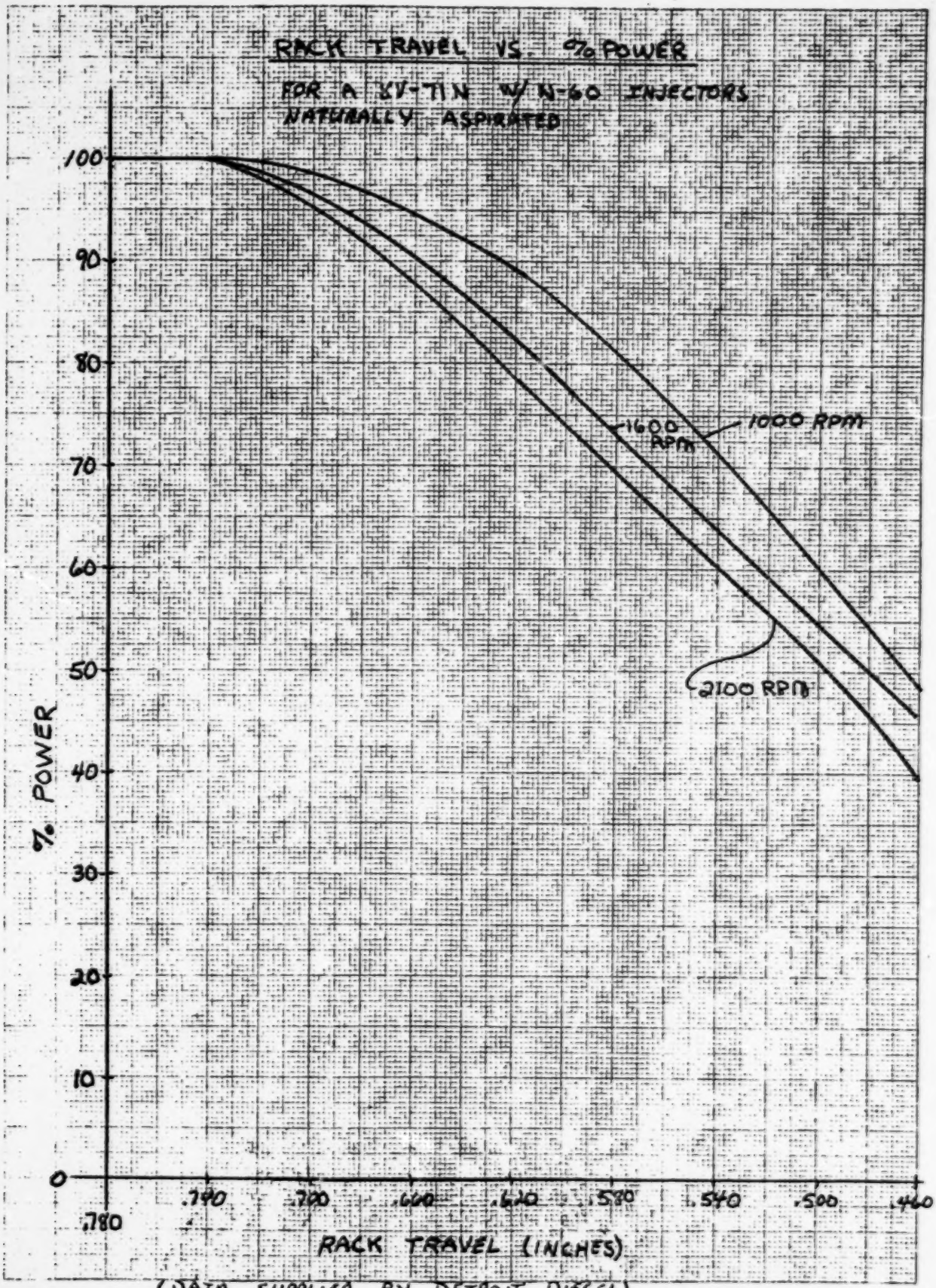
Eq. Number	REGRESSION COEFFICIENTS $\log_{10}$ RPM	$\%RACK^{1.56}$ ($\log_{10}$ RPM)	Constant	Variance of Estimate	Std. Error of Estimate	Multiple Correlation Coefficient	Coefficient of Determination
1	-22.303	$-.44663 \times 10^{-1}$	173.16	13.7196	3.7040	.9923	.9847
2	-22.507	$-.44802 \times 10^{-1}$	173.90	13.1062	3.6202	.9933	.9866

The final constraint sets the maximum RPM value at 2400. This value was decided upon after consultation with DDA engineers. In other words, the maximum attainable RPM value, assuming the governor is operating properly, is 2400 rpm. The governor will prevent the engine from running at speeds greater than this value. Thus, at 2400 rpm the engine will put out 0% HP. The above constraint is necessary since operation above 2400 rpm is impossible unless the engine is being motored. No motoring above 2400 rpm was observed in the CAPE-21 data for the DDA engines surveyed.

There is another underlying assumption that is made in applying equation 3 as a % HP model for DDA diesel engine. That is, degradation and subsequently % HP variation from engine to engine is assumed to be small. The % HP model in equation 3 was derived from data taken on a relatively new engine. This model will be applied indiscriminately to all DDA diesel engines in the CAPE-21 survey. Thus, the % HP model is assumed valid for all naturally aspirated DDA diesel engines equipped with N-65 injectors regardless of age. Also, the surveyed engines are assumed to be in proper operating condition. DDA engineers felt these assumptions reasonable, therefore the assumptions are used.

Finally, due to lack of data and schedule restraints the % HP model as represented in equation 3 will be also applied to the two turbocharged (w/N-65 injectors) engines surveyed in Los Angeles, and the six naturally aspirated engines with unknown injector types surveyed in New York City. Equation 3, as stated earlier was developed for naturally aspirated engines (6 or 8 cyl) with N-65 injectors. (DDA told EPA engineers that the number of cylinders should not alter the % HP relationship as long as the engine is of the same type and has the same injectors (e.g., L.A. truck No. 6 and N.Y.C. truck No. 42)). Figures 5 and 6 demonstrate the relationship of engine load versus injector rack position for a naturally aspirated and a turbocharged engine. Although the injectors are different for the engines, the trends are still accurate and of interest. As Figure 6 demonstrates, the turbocharged engine has much tighter lines of constant rpm. DDA engineers suggested that perhaps these characteristic curves are a result of A/F ratio changes.

By using equation 3 for % HP prediction for the two turbocharged engines (in L.A.), inaccuracies in % HP prediction will surely result. Although errors in % HP values cannot be accurately quantified due to lack of data, they are expected to be minimal. After all, equation 3 will approximate the proper trends for % HP versus % rack position and rpm. From Figures 5 and 6, the errors involved in using a naturally aspirated % HP model for a turbocharged engine appear to be small at low loads and somewhat larger at high loads due to the tighter lines of constant rpm for the turbocharged engine as described above.



(DATA SUPPLIED BY DETROIT DIESEL).

10 X 10 TO THE CENTIMETER 18 X 25 CM.
KEUFFEL & ESSER CO. - LINE-FLO CONVERTERS & PRINTERS

FIGURE 5

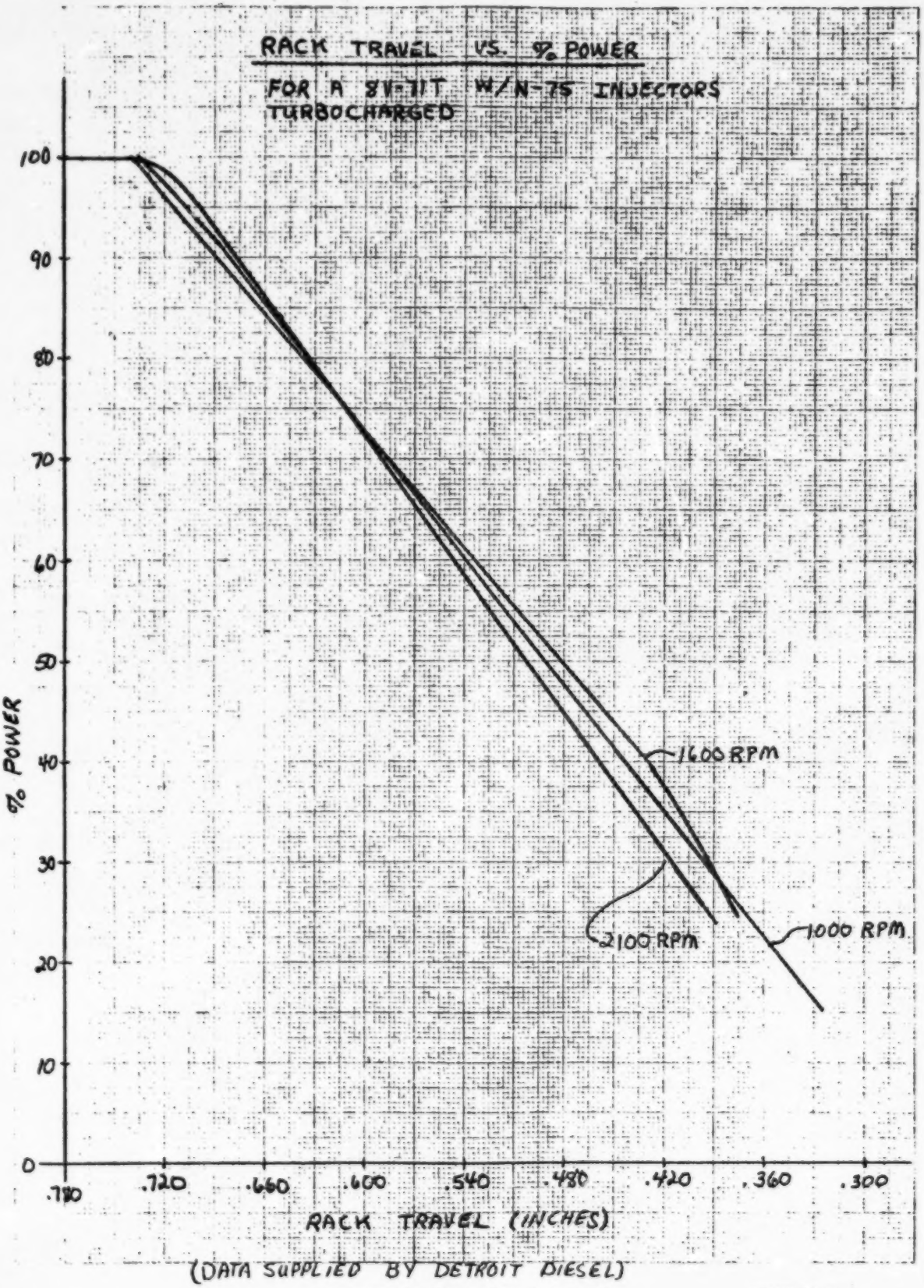

RACK TRAVEL VS. % POWER
FOR A 8V-71T W/N-75 INJECTORS
TURBOCHARGED
100
90
80
70
60
50
40
30
20
10
0
% POWER
1600 RPM
2100 RPM
1000 RPM
.780
.720
.660
.600
.540
.480
.420
.360
.300
RACK TRAVEL (INCHES)
(DATA SUPPLIED BY DETROIT DIESEL)

FIGURE 6

For the six naturally aspirated engines with unknown injectors, the use of equation 3 should provide a fair estimation of % HP. Figure 7 illustrates % theoretical output versus % rack travel for six different injectors. Variations among the different injectors occur at all load conditions. The variation becomes more substantial at heavy loads. However, not knowing the injectors of the six New York City engines, there is no other alternative but to assume they are N-65's. Should their injectors not be N-65, some inaccuracy in % HP prediction can be expected as demonstrated by Figure 7. The inaccuracies encountered are expected to be minimal. After all, the variation among the different injectors does fall within a narrow bandwidth.

D. Summary and Conclusions

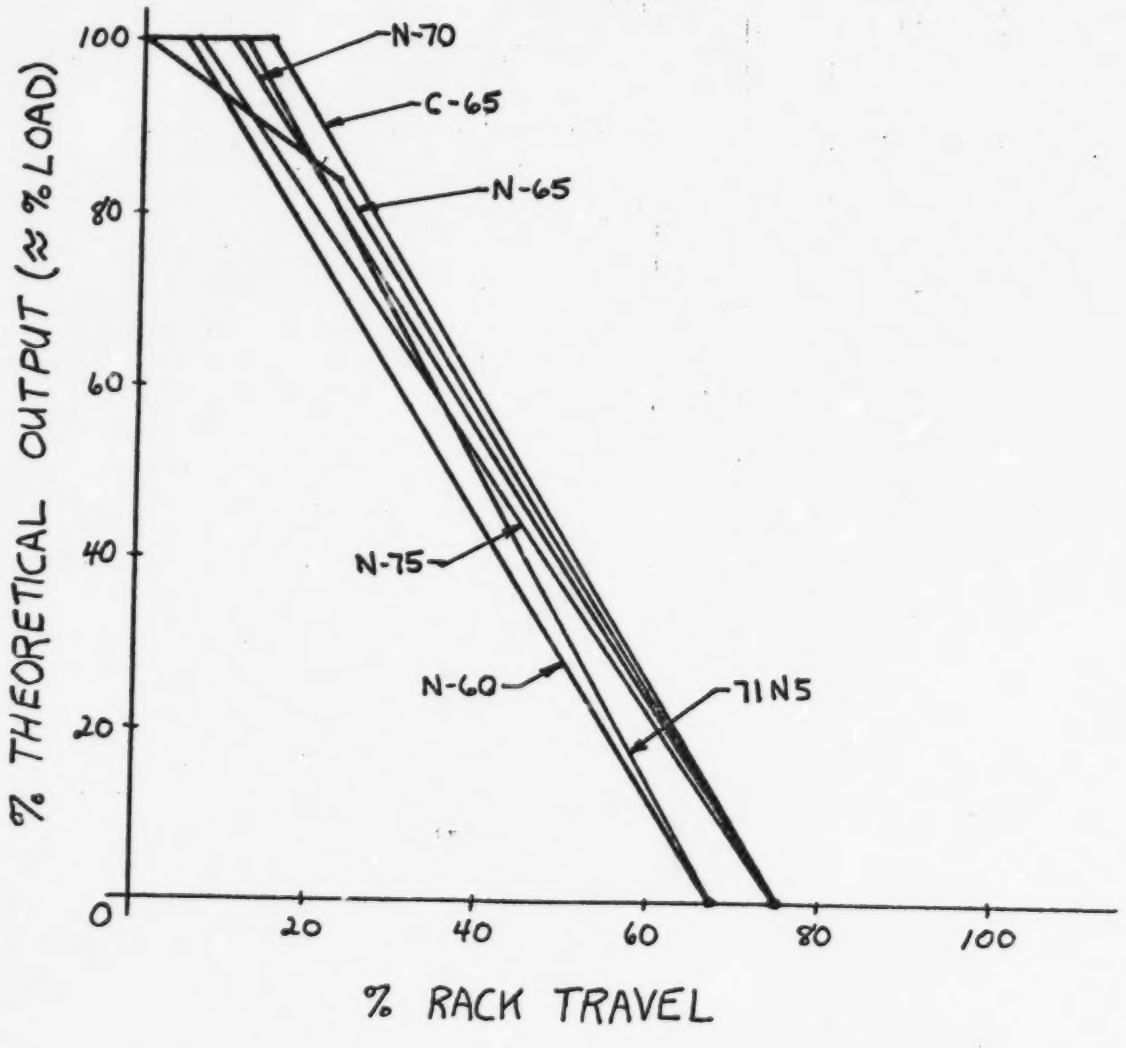
In summarization, data was collected from a naturally aspirated 8V-71N equipped with N-65 injectors and analyzed. The result being a % HP model to predict % engine HP from % rack travel and engine rpm. The equation is shown below.

$$\%HP = -22.507\ (\log_{10} RPM) - .44802 \times 10^{-1}\ (\%\ RACK^{1.56})\ (\log_{10} RPM) + 173.90$$

This equation will be used for all naturally aspirated Detroit Diesel engines equipped with N-65 injectors. Additionally, the % HP model above will be used to predict % engine horsepower for the six naturally aspirated DDA engines with unknown injector types and the two turbocharged engines (equipped with N-65 injectors). For the six naturally aspirated engines in New York City the injector types were not available. Consequently, the only alternative is to assume they were equipped with N-65 injectors and apply the % HP model to the data from these engines. For the two turbocharged DDA engines, no other data was available to accurately develop a % HP model. Thus, being bound with schedule constraints, the decision was made to use the % HP model derived for the naturally aspirated DDA engines for the turbocharged engines. Of course, by doing this same inaccuracies will be introduced, particularily at high load conditions. These inaccuracies are not expected to be large as shown by the small variation in injector response plotted in Figure 7.

In conclusion, the model developed for % HP calculation for the CAPE-21 DDA engine equipped trucks demonstrates very good prediction accuracy. The model development was based on the latest available data. The model will provide accurate % HP estimation for the great majority of the DDA engines surveyed during the conduct of the CAPE-21 survey.

% RACK TRAVEL VS. % THEORETICAL OUTPUT
FOR VARIOUS INJECTORS



(DATA SUPPLIED BY DETROIT DIESEL)

FIGURE 7

V. Caterpillar Diesel Engine Horsepower Model Development

A. Introduction

During the CAPE-21 survey only two Caterpillar engines were tested. Both were surveyed in Los Angeles. Below are the descriptions of the engines.

Table 17

Caterpillar Diesel Engines

Los Angeles Survey

Truck No.	Model Year	Engine Model	Engine Serial Number
16	1968	1160 (Ford V225)	95 R 314
18	1972	1140 (Ford V150)	36 B 1936

For these two engines, engine power output was recorded by measuring throttle travel. In attempting to characterize the relationship between % engine HP and % throttle position, Caterpillar Tractor Co.'s help and recommendations were solicited. Since these engines are no longer produced in their former configurations, actual testing was out of the question due to lack of availability. Consequently, Caterpillar Tractor Co. engineers offered to research their files for any data on these two engines which may have enabled a % throttle position versus % HP relationship to be developed.

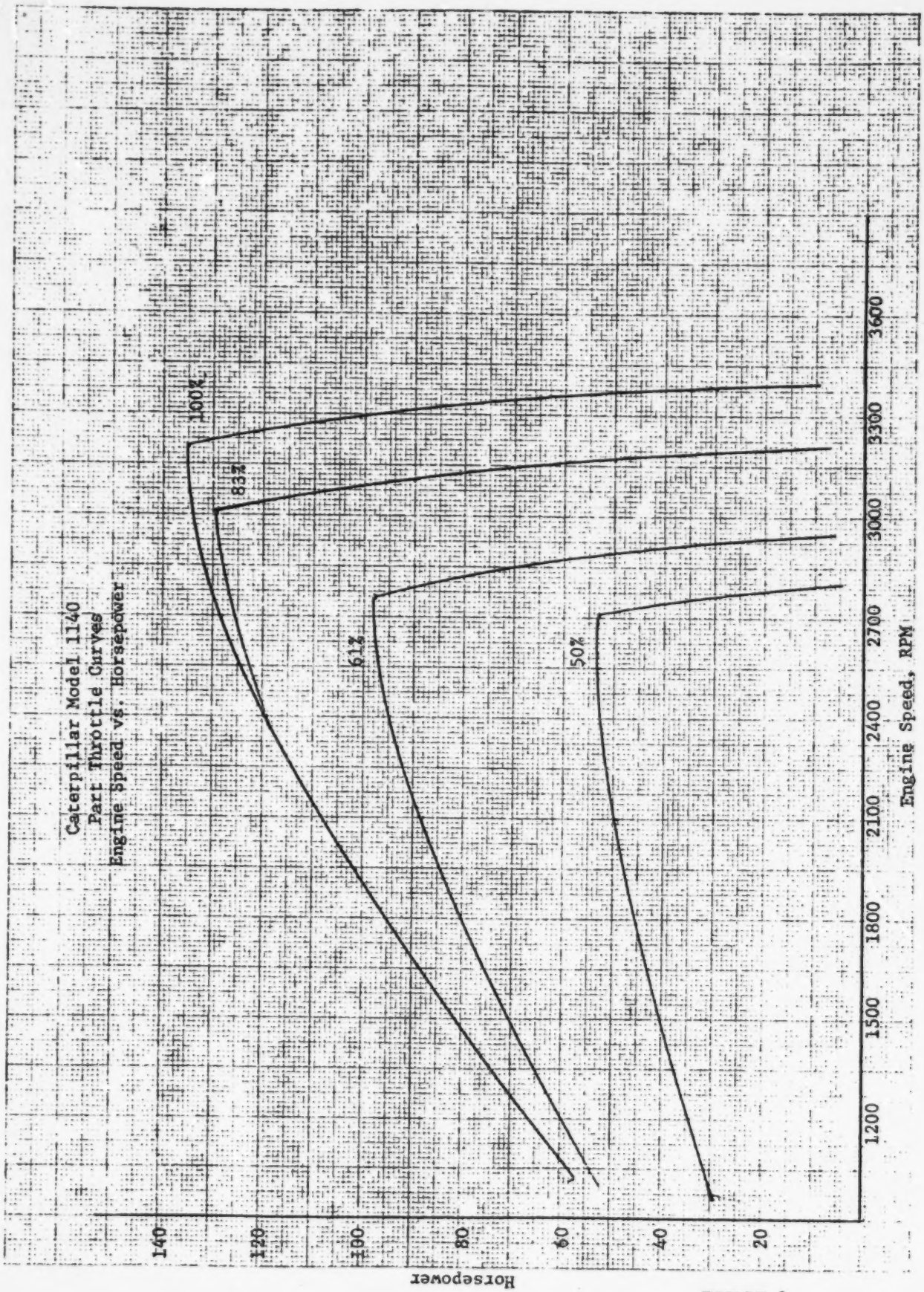
Figures 8 and 9 are plots of all the data Caterpillar found on these engines. Except for lower rpm values (rpm < 1200), the curves appeared to provide an adequate basis for developing an analytical model for % HP.

B. Data Analysis

Due to the lack of data below 1200 rpm, the curves were replotted with extrapolations below 1200 rpm. Figures 10 and 11 demonstrate the results.

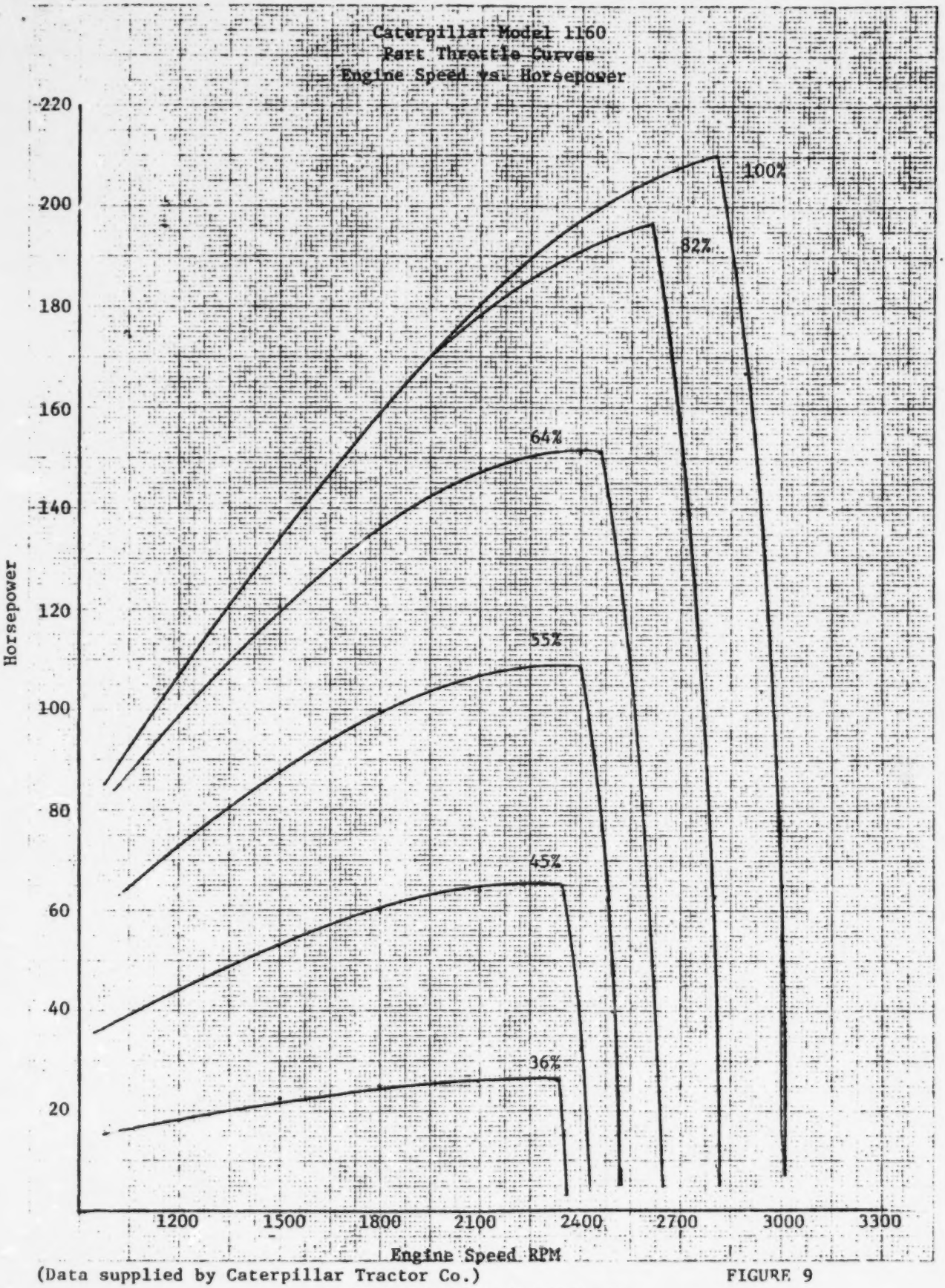
Of course, Caterpillar was consulted before this was done. Since no other data was available for these engines, Caterpillar agreed that extrapolation was reasonable.

These plots were provided to our cycle development contractor, Olson Labs, for % HP model development.



(Data supplied by Caterpillar Tractor Co.)

FIGURE 8



(Data supplied by Caterpillar Tractor Co.)

FIGURE 9

10 X 10 TO THE CENTIMETER (4 X 4 TO THE INCH)
KEUFFEL & ESSER CO.

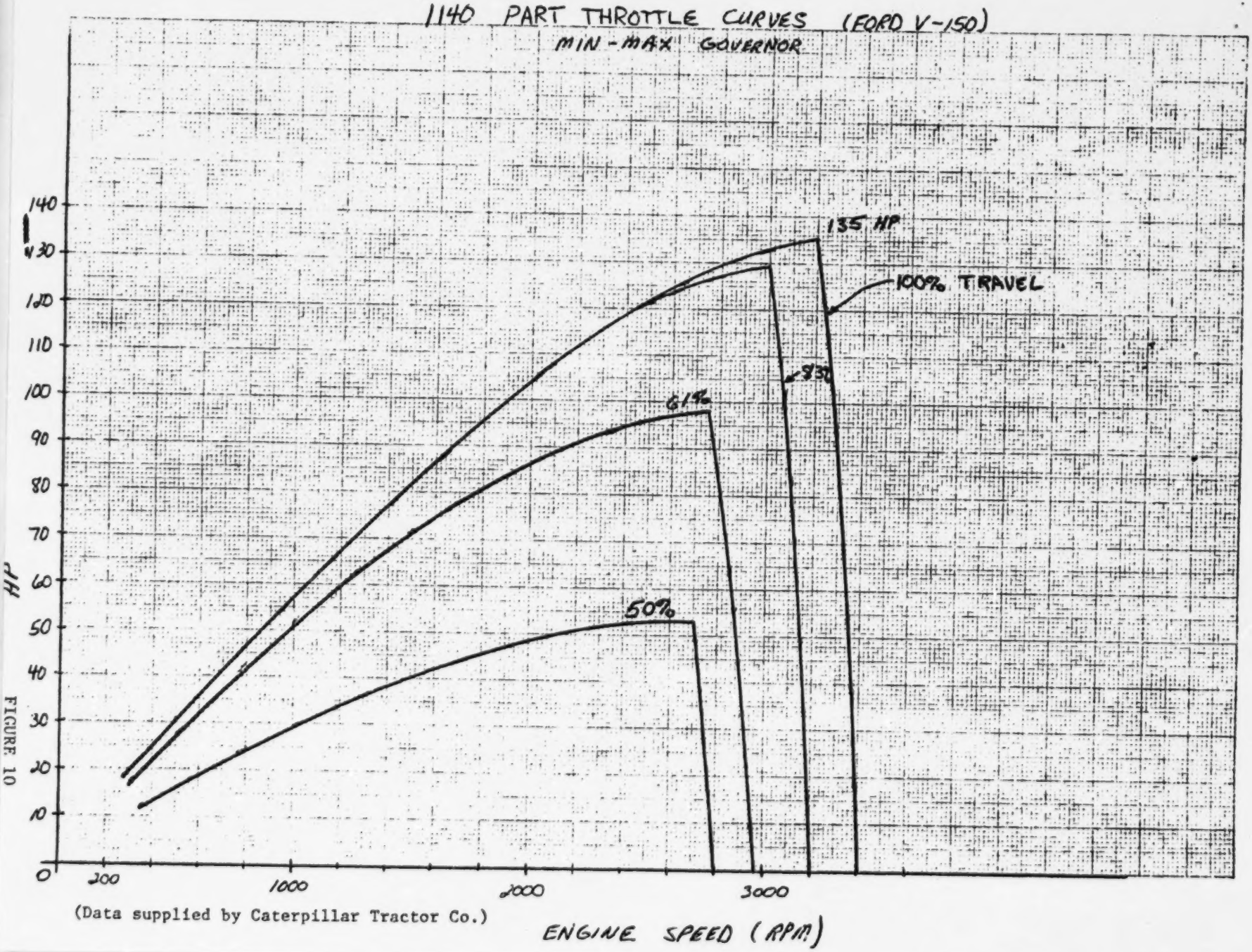
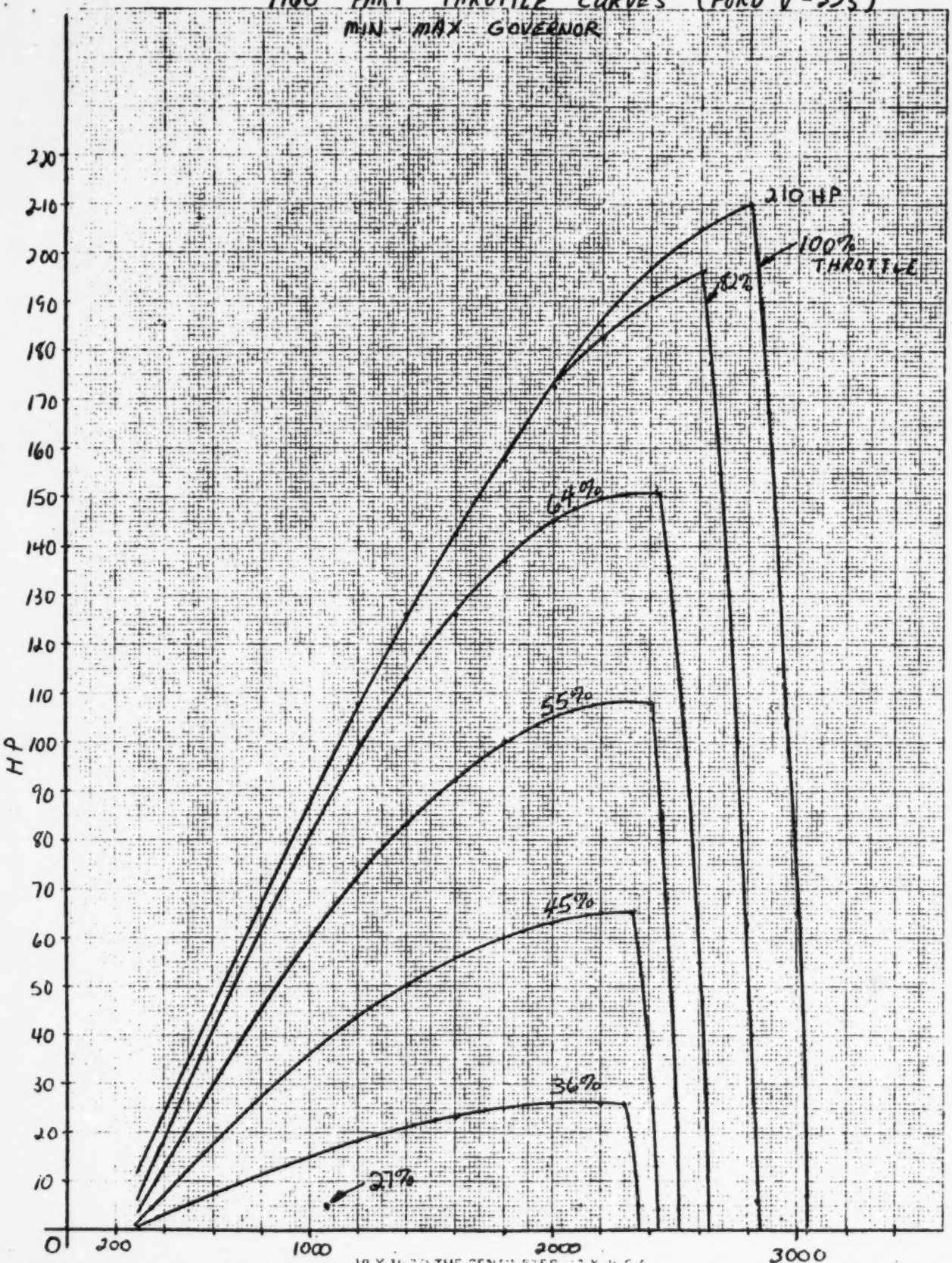


FIGURE 10

(Data supplied by Caterpillar Tractor Co.)



(Data supplied by Caterpillar Tractor Co.)

FIGURE 11

The contractor then proceeded to perform a regression analysis on the data. EPA personnel also did a parallel data analysis. Both analyses proved futile, for no adequate analytical expression could be derived to characterize the data in Figures 10 and 11.

The only alternative remaining was to read the data from the graphs visually, and form a matrix from the data. Table 18 illustrates the end result of this effort. Interpolation was used to obtain values of % horsepower between the curves in Figures 10 and 11. Extrapolation was used to obtain values of % horsepower beyond the curves. Along the top of the matrices is % throttle in 2% increments. (Throttle travel is normalized to the maximum throttle travel). Along the sides of the matrices is rpm in 50 rpm increments. Within the bodies of the matrice are % horsepower values. The horsepower values are all normalized to the maximum horsepower at each rpm.

To use the matrices, a % throttle value and rpm must be known. Knowing both values, a % horsepower corresponding to these values is read from the body of the matrix.

C. Discussion

The matrices discussed above are as accurate as the data supplied by Caterpillar Tractor Co. There are however, some limitations in the characterization of power for the two Caterpillar engines. Most importantly is the limitation of the data itself. For example, no data was available for operation less than 1200 rpm. Also, power data for throttle positions of low values (less than 30%) was absent. Therefore, extrapolations had to be made not only below 1200 rpm for all % throttle's, but also for % throttle positions less than 36% for the 1160 and 50% for the 1140 (at all values of rpm). Due to the limited nature of the data the extrapolations (and interpolations) were necessarily linear.

Another source for inaccuracies is introduced by the format of the matrices. The interval width for rpm is 50 rpm, and for % throttle it is 2%. Therefore slight round off errors will occur when rpm and % throttle fall between values on the matrices. The errors encountered could reasonably be expected to be unimportant. After all, there are 50 categories of % throttle and 60 to 64 categories of rpm for the two engines.

Finally, in using the matrices to predict % horsepower, motoring cannot be identified. Therefore part throttle motoring cannot be identified. A portion of the motoring will be assigned positive power values, when in reality the engine power output is zero. However, preliminary CAPE-21 results indicate that a good portion of engine motoring is performed with closed throttle. Thus, errors introduced by not identifying part throttle motoring are expected to be small.

TABLE 18 (1 of 4)

CATERPILLAR % HP MATRIX

CODE 1 = MODEL 1140
CODE 2 = MODEL 1160

CODE 1=1140 2=1160	RPM	% THROTTLE 2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
1	1 300	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	7	13	19	25	31	37	43	49	56
2	1 350	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	8	14	20	25	31	37	43	49	55
3	1 400	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	13	20	27	34	40	47	54
4	1 450	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	9	15	22	29	35	42	49	56
5	1 500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	13	20	27	33	40	47	53
6	1 550	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	8	15	22	29	36	43	49	56
7	1 600	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	14	21	27	34	41	47	54
8	1 650	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	9	17	24	31	38	46	53
9	1 700	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	11	19	26	33	40	48	55
10	1 750	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	10	17	24	31	38	45	52
11	1 800	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	10	17	24	31	38	45	52
12	1 850	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	13	20	27	34	41	47	54
13	1 900	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	10	17	25	32	39	46	53
14	1 950	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	11	18	25	32	39	46	53
15	11000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	11	18	25	32	39	46	53
16	11050	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	10	17	25	32	39	46	53
17	11100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	10	17	24	31	38	45	52
18	11150	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	9	16	23	30	37	45	52
19	11200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	8	16	23	30	37	44	51
20	11250	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	8	15	22	29	37	44	51
21	11300	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	8	15	22	29	36	44	51
22	11350	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	14	21	29	36	43	50
23	11400	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	14	21	28	36	43	50
24	11450	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	14	21	28	35	42	49
25	11500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	8	15	22	29	35	42	49
26	11550	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	14	21	28	35	42	49
27	11600	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	14	21	28	35	42	49
28	11650	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	8	15	22	29	36	43	49
29	11700	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	8	15	21	28	35	42	49
30	11750	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	8	15	22	28	35	42	48
31	11800	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	13	20	27	34	41	47
32	11850	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	13	20	27	34	41	47
33	11900	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	14	20	27	34	41	47
34	11950	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	7	14	21	27	34	40	47
35	12000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	13	20	26	33	40	46
36	12050	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	7	14	20	27	33	40	46
37	12100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	13	19	26	32	39	45
38	12150	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	13	20	26	33	39	45
39	12200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	8	14	20	27	33	39	46
40	12250	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	12	19	25	32	38	45
41	12300	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	12	18	25	31	38	44
42	12350	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	13	19	25	32	38	44
43	12400	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	12	18	25	31	38	44
44	12450	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	11	17	24	30	37	43
45	12500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	10	17	23	30	36	43
46	12550	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	11	18	24	30	37	43
47	12600	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	10	17	23	30	36	43
48	12650	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	10	17	23	29	36	42
49	12700	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	10	16	22	29	35	42
50	12750	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	11	19	28
51	12800	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
52	12850	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
53	12900	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
54	12950	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
55	13000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
56	13050	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
57	13100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
58	13150	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
59	13200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60	13250	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

INTERVAL LIMITS:

% THROTTLE, 1% ≤ 2% < 3%,
3% ≤ 4% < 5%,
5% ≤ 6% < 7%, etc.

% RPM, 0 ≤ 300 < 325,
325 ≤ 350 < 375,
375 ≤ 400 < 425, etc.

% THROTTLE

TABLE 18 (2 of 4)

CODE 1=1140 2=1160	RPM	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
61	13300	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
62	13350	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
63	13400	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
64	13450	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
65	2 300	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	5	6	8	9	11	13	15	17	20	23
66	2 350	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4	6	9	12	14	17	19	22	26	31	35
67	2 400	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	5	9	13	17	21	25	29	33	38	43
68	2 450	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	9	13	18	22	27	31	36	40	45
69	2 500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	5	10	14	19	23	28	32	37	42	47
70	2 550	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	10	15	20	25	30	35	40	45	50
71	2 600	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	10	16	21	26	32	37	43	48	53
72	2 650	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	10	16	21	26	31	37	42	47	53
73	2 700	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	6	11	16	21	26	32	37	42	47	53
74	2 750	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	11	16	21	27	32	37	42	48	53
75	2 800	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	11	16	22	27	32	38	43	48	54
76	2 850	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	11	16	22	27	33	38	44	49	54
77	2 900	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	11	17	22	28	33	39	44	50	55
78	2 950	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	6	12	17	22	28	33	38	44	49	54
79	21000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	7	12	17	23	28	33	39	44	50	55
80	21050	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	7	12	17	23	28	33	39	44	49	55
81	21100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	7	12	17	23	28	33	38	43	49	54
82	21150	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	11	17	22	28	33	38	44	49	54
83	21200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	6	11	17	22	28	33	38	44	49	55
84	21250	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	6	12	17	22	28	33	38	44	49	54
85	21300	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	7	12	17	22	28	33	38	43	49	54
86	21350	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	6	11	16	22	27	32	38	43	48	53
87	21400	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	6	12	17	22	27	32	37	42	48	53
88	21450	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	7	12	17	22	27	32	37	43	48	53
89	21500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	6	11	16	21	27	32	37	42	47	52
90	21550	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	7	12	17	22	26	31	36	41	47	52
91	21600	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	6	11	16	21	27	32	37	42	47	52
92	21650	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	6	11	16	21	26	31	36	41	46	51
93	21700	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	6	11	16	21	26	31	36	41	46	51
94	21750	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	6	11	16	21	26	31	36	41	45	50
95	21800	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	6	11	16	21	26	31	36	41	46	51
96	21850	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	6	10	15	20	25	30	35	40	45	50
97	21900	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	6	11	16	20	25	30	35	40	45	50
98	21950	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	6	10	15	20	25	30	35	39	44	49
99	22000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	6	10	15	20	25	29	34	39	44	49
100	22050	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	10	15	19	24	29	34	38	43	48
101	22100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	10	14	19	24	29	33	38	43	48
102	22150	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	9	14	19	24	28	33	38	42	47
103	22200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	9	14	19	23	28	33	37	42	47
104	22250	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	9	14	18	23	27	32	36	41	46
105	22300	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	9	14	18	23	27	32	36	41	45
106	22350	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	8	13	18	23	28	33	38	43
107	22400	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	15	22	29	37
108	22450	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	15	22
109	22500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
110	22550	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
111	22600	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
112	22650	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
113	22700	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
114	22750	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
115	22800	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
116	22850	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
117	22900	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
118	22950	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
119	23000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
120	23050	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

% THROTTLE

TABLE 18 (3 of 4)

CODE 1=1140 2=1160	RPM	52	54	56	58	60	62	64	66	68	70	72	74	76	78	80	82	84	86	88	90	92	94	96	98	100
1	1 300	62	68	74	80	86	89	91	92	92	93	94	96	97	97	98	99	100	100	100	100	100	100	100	100	100
2	1 350	60	66	72	78	84	87	88	90	91	92	93	95	95	97	98	100	100	100	100	100	100	100	100	100	100
3	1 400	61	68	75	81	88	92	93	94	94	95	96	97	97	98	99	100	100	100	100	100	100	100	100	100	100
4	1 450	62	69	76	83	89	93	94	94	95	96	96	97	98	98	99	100	100	100	100	100	100	100	100	100	100
5	1 500	60	67	73	80	87	90	91	92	93	94	95	96	97	98	99	100	100	100	100	100	100	100	100	100	100
6	1 550	63	70	77	83	90	94	95	95	96	96	97	97	98	98	99	100	100	100	100	100	100	100	100	100	100
7	1 600	61	68	75	81	88	92	93	93	94	95	96	97	97	98	99	100	100	100	100	100	100	100	100	100	100
8	1 650	60	67	74	81	88	92	93	94	95	95	96	97	97	98	99	100	100	100	100	100	100	100	100	100	100
9	1 700	62	70	77	84	91	95	96	96	97	97	98	98	98	99	99	100	100	100	100	100	100	100	100	100	100
10	1 750	59	66	73	80	88	91	92	93	94	95	95	96	97	98	99	100	100	100	100	100	100	100	100	100	100
11	1 800	59	66	73	81	88	92	92	93	94	95	96	97	97	98	99	100	100	100	100	100	100	100	100	100	100
12	1 850	61	68	75	81	88	92	93	94	94	95	96	97	97	98	99	100	100	100	100	100	100	100	100	100	100
13	1 900	60	67	74	81	89	93	93	94	95	95	96	97	97	98	99	100	100	100	100	100	100	100	100	100	100
14	1 950	60	67	74	81	87	91	92	93	94	95	95	96	97	98	99	100	100	100	100	100	100	100	100	100	100
15	11000	60	67	74	81	88	92	92	93	94	95	96	96	97	98	99	100	100	100	100	100	100	100	100	100	100
16	11050	61	68	75	82	89	93	94	95	95	96	97	97	98	98	99	100	100	100	100	100	100	100	100	100	100
17	11100	60	67	74	81	88	92	93	94	94	95	96	97	97	98	99	100	100	100	100	100	100	100	100	100	100
18	11150	59	66	73	80	87	91	92	93	94	95	95	96	97	98	99	100	100	100	100	100	100	100	100	100	100
19	11200	58	65	72	79	86	90	91	92	93	94	95	96	97	98	99	100	100	100	100	100	100	100	100	100	100
20	11250	58	65	72	79	86	90	91	92	93	94	95	96	97	98	99	100	100	100	100	100	100	100	100	100	100
21	11300	58	65	72	79	87	91	92	92	93	94	95	96	97	98	99	100	100	100	100	100	100	100	100	100	100
22	11350	57	64	71	79	86	90	91	92	93	94	95	96	97	98	99	100	100	100	100	100	100	100	100	100	100
23	11400	57	64	72	79	86	90	91	92	93	94	95	96	97	98	99	100	100	100	100	100	100	100	100	100	100
24	11450	56	64	71	78	85	89	90	91	92	93	94	95	96	97	98	99	100	100	100	100	100	100	100	100	100
25	11500	56	63	70	77	84	88	89	90	92	93	94	95	96	97	98	99	100	100	100	100	100	100	100	100	100
26	11550	56	63	70	77	84	89	90	91	92	93	94	95	96	97	98	99	100	100	100	100	100	100	100	100	100
27	11600	56	63	70	77	84	88	89	90	91	92	94	95	96	97	98	99	100	100	100	100	100	100	100	100	100
28	11650	56	63	70	77	84	88	89	90	91	93	94	95	96	97	98	99	100	100	100	100	100	100	100	100	100
29	11700	56	63	69	76	83	87	88	90	91	92	93	95	96	97	98	99	100	100	100	100	100	100	100	100	100
30	11750	55	62	68	75	82	86	87	88	90	91	92	94	95	97	98	99	100	100	100	100	100	100	100	100	100
31	11800	54	61	68	75	82	86	87	89	90	91	93	94	95	97	98	99	100	100	100	100	100	100	100	100	100
32	11850	54	61	68	75	82	86	88	89	90	91	93	94	95	97	98	99	100	100	100	100	100	100	100	100	100
33	11900	54	61	68	75	81	86	87	88	90	91	92	94	95	97	98	99	100	100	100	100	100	100	100	100	100
34	11950	54	60	67	73	80	84	86	87	89	90	92	93	95	96	98	99	100	100	100	100	100	100	100	100	100
35	12000	53	59	66	73	79	83	85	87	88	90	91	93	95	96	98	99	100	100	100	100	100	100	100	100	100
36	12050	53	59	66	72	79	83	85	86	88	89	91	93	94	96	98	99	100	100	100	100	100	100	100	100	100
37	12100	52	59	65	72	78	82	84	86	87	89	91	92	94	96	98	99	100	100	100	100	100	100	100	100	100
38	12150	52	58	65	71	78	82	84	85	87	89	90	92	94	96	97	99	100	100	100	100	100	100	100	100	100
39	12200	52	58	65	71	77	81	83	85	87	88	90	92	94	96	97	99	100	100	100	100	100	100	100	100	100
40	12250	52	58	65	72	78	82	84	86	87	89	91	92	94	96	97	99	100	100	100	100	100	100	100	100	100
41	12300	51	57	64	70	77	81	83	85	86	88	90	92	94	95	97	99	100	100	100	100	100	100	100	100	100
42	12350	51	57	64	70	76	80	82	84	86	88	90	92	94	95	97	99	100	100	100	100	100	100	100	100	100
43	12400	51	57	63	70	76	81	82	84	86	88	90	92	94	95	97	99	100	100	100	100	100	100	100	100	100
44	12450	50	56	63	69	76	80	82	84	86	88	90	92	93	95	97	99	100	100	100	100	100	100	100	100	100
45	12500	50	56	63	69	76	80	82	84	86	88	90	92	93	95	97	99	100	100	100	100	100	100	100	100	100
46	12550	49	56	62	69	75	79	81	83	85	87	89	91	92	94	96	98	99	99	99	100	100	100	100	100	100
47	12600	49	56	62	69	75	79	81	83	85	87	89	91	92	94	96	98	99	99	99	100	100	100	100	100	100
48	12650	48	55	61	67	74	78	80	82	84	86	88	90	92	94	95	97	98	99	99	99	99	99	99	100	100
49	12700	48	55	61	67	74	78	80	82	84	86	88	90	92	94	96	97	99	99	99	99	99	99	99	100	100
50	12750	37	46	55	63	72	78	80	82	84	86	88	89	91	93	95	97	99	99	99	99	99	99	99	100	100
51	12800	18	30	39	49	57	66	73	79	82	85	87	90	92	94	96	98	98	98	99	99	99	99	100	100	100
52	12850	0	6	20	30	40	50	59	67	74	82	85	88	91	94	97	97	98	98	98	98	98	99	99	99	100
53	12900	0	0	0	9	21	31	42	51	60	68	79	91	93	94	95	97	97	97	98	98	98	99	99	100	100
54	12950	0	0	0	0	0	8	19	31	41	51	62	75	79	94	96	97	97	97	98	98	99	99	99	100	100
55	13000	0	0	0	0	0	0	0	7	19	30	42	55	69	79	88	97	97	97	98	98	99	99	99	100	100
56	13050	0	0	0	0	0	0	0	0	0	6	19	32	46	59	71	83	91	98	98	99	99	99	99	100	100
57	13100	0	0	0	0	0	0	0	0	0	0	0	4	19	33	48	63	73	81	89	96	99	99	100	100	100
58	13150	0	0	0	0	0	0	0	0	0	0	0	0	0	0	19	37	49	59	69	80	87	93	97	100	100
59	13200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16	31	43	56	65	73	76	92	100
60	13250	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	30	44	57	73	87	100	

CODE
1 = 1160
2 = 1160

% THROTTLE

TABLE 18 (4 OF 4)

	RPM	52	54	56	58	60	62	64	66	68	70	72	74	76	78	80	82	84	86	88	90	92	94	96	98	100
61	13300	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	28	53	78	100	
62	13350	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	54	100	
63	13400	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	
64	13450	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
65	2 300	26	29	33	38	44	48	54	59	64	69	75	79	85	90	95	100	100	100	100	100	100	100	100	100	100
66	2 350	40	45	51	57	64	70	76	79	82	84	87	89	92	95	98	100	100	100	100	100	100	100	100	100	100
67	2 400	49	54	59	64	69	73	78	81	83	86	88	90	93	95	97	100	100	100	100	100	100	100	100	100	100
68	2 450	50	54	59	64	70	75	80	82	84	87	89	91	93	96	98	100	100	100	100	100	100	100	100	100	100
69	2 500	52	57	63	69	74	80	86	87	89	91	92	94	95	97	98	100	100	100	100	100	100	100	100	100	100
70	2 550	55	60	65	72	78	84	90	91	92	93	95	95	97	98	99	100	100	100	100	100	100	100	100	100	100
71	2 600	59	64	69	74	79	84	89	90	91	93	94	95	96	98	99	100	100	100	100	100	100	100	100	100	100
72	2 650	58	64	69	75	81	86	92	93	94	95	96	96	97	98	99	100	100	100	100	100	100	100	100	100	100
73	2 700	58	63	69	74	80	86	91	92	93	94	95	96	97	98	99	100	100	100	100	100	100	100	100	100	100
74	2 750	59	64	69	75	80	85	90	92	93	94	95	96	97	98	99	100	100	100	100	100	100	100	100	100	100
75	2 800	59	64	70	75	80	86	91	92	93	94	95	96	97	98	99	100	100	100	100	100	100	100	100	100	100
76	2 850	59	65	70	75	81	86	92	93	94	95	95	96	97	98	99	100	100	100	100	100	100	100	100	100	100
77	2 900	61	66	71	77	82	87	92	93	94	95	96	96	97	98	99	100	100	100	100	100	100	100	100	100	100
78	2 950	60	65	70	76	82	87	93	94	94	95	96	97	98	98	99	100	100	100	100	100	100	100	100	100	100
79	21000	61	66	72	77	82	88	93	94	95	95	96	97	98	99	99	100	100	100	100	100	100	100	100	100	100
80	21050	60	66	71	76	82	87	92	93	94	95	96	97	97	98	99	100	100	100	100	100	100	100	100	100	100
81	21100	59	65	70	76	81	86	92	93	94	95	96	96	97	98	99	100	100	100	100	100	100	100	100	100	100
82	21150	60	65	70	76	81	87	92	93	94	95	96	96	97	98	99	100	100	100	100	100	100	100	100	100	100
83	21200	60	66	71	76	81	86	92	93	93	94	95	96	97	98	99	100	100	100	100	100	100	100	100	100	100
84	21250	60	65	70	76	81	86	91	92	93	94	95	96	97	98	99	100	100	100	100	100	100	100	100	100	100
85	21300	59	65	70	75	81	86	91	92	93	94	95	96	97	98	99	100	100	100	100	100	100	100	100	100	100
86	21350	59	64	69	74	80	85	90	91	92	93	95	96	97	98	99	100	100	100	100	100	100	100	100	100	100
87	21400	58	63	68	74	79	84	90	91	92	93	94	95	97	98	99	100	100	100	100	100	100	100	100	100	100
88	21450	58	64	69	74	80	85	91	92	93	94	95	96	97	98	99	100	100	100	100	100	100	100	100	100	100
89	21500	57	63	68	73	79	84	90	91	92	93	94	95	97	98	99	100	100	100	100	100	100	100	100	100	100
90	21550	57	62	67	73	78	84	89	90	92	93	94	95	96	98	99	100	100	100	100	100	100	100	100	100	100
91	21600	57	62	68	73	78	84	89	91	92	93	94	95	96	98	99	100	100	100	100	100	100	100	100	100	100
92	21650	56	61	67	72	78	83	88	90	91	92	94	95	96	97	99	100	100	100	100	100	100	100	100	100	100
93	21700	56	61	67	72	77	83	88	89	91	92	93	95	96	97	99	100	100	100	100	100	100	100	100	100	100
94	21750	55	60	65	71	77	82	88	89	90	92	93	95	96	97	99	100	100	100	100	100	100	100	100	100	100
95	21800	56	61	66	71	76	82	87	88	90	91	93	94	96	97	99	100	100	100	100	100	100	100	100	100	100
96	21850	55	60	65	70	76	81	86	88	89	91	92	94	95	97	99	100	100	100	100	100	100	100	100	100	100
97	21900	55	60	65	70	75	80	86	87	89	90	92	94	95	97	98	100	100	100	100	100	100	100	100	100	100
98	21950	54	59	64	69	74	79	85	86	88	90	92	93	95	97	98	100	100	100	100	100	100	100	100	100	100
99	22000	53	58	63	68	74	79	84	86	87	89	91	93	95	96	98	100	100	100	100	100	100	100	100	100	100
100	22050	52	57	62	67	72	77	83	84	86	88	90	92	94	96	98	100	100	100	100	100	100	100	100	100	100
101	22100	52	57	62	67	72	77	82	84	86	88	90	91	93	95	97	99	99	99	99	99	100	100	100	100	100
102	22150	51	56	61	66	71	76	81	83	85	87	89	91	93	95	96	98	99	99	99	99	99	99	100	100	100
103	22200	51	56	61	66	71	76	81	83	85	87	89	90	92	94	96	98	99	99	99	99	99	99	100	100	100
104	22250	50	55	59	64	69	74	79	81	83	85	87	89	91	93	95	97	98	98	98	99	99	99	99	100	100
105	22300	50	54	59	64	69	74	79	81	83	85	87	89	91	93	95	97	98	98	98	99	99	99	99	100	100
106	22350	48	53	58	63	68	73	77	80	82	84	86	88	90	93	95	97	97	98	98	98	99	99	99	100	100
107	22400	44	51	57	62	67	72	77	79	81	83	85	88	90	92	94	96	97	97	98	98	98	99	99	100	100
108	22450	29	37	44	51	58	66	73	75	78	81	83	86	89	91	94	96	97	97	98	98	98	99	99	100	100
109	22500	2	10	20	33	42	53	63	71	77	82	87	89	90	92	94	96	96	97	97	98	98	99	99	100	100
110	22550	0	0	0	0	17	34	48	59	66	72	79	86	91	92	94	96	97	97	97	98	98	99	99	100	100
111	22600	0	0	0	0	0	7	27	40	50	57	66	75	80	85	91	96	96	97	97	98	98	99	99	100	100
112	22650	0	0	0	0	0	0	0	10	25	36	48	58	66	72	78	85	91	98	98	98	99	99	99	100	100
113	22700	0	0	0	0	0	0	0	0	0	3	21	34	45	49	60	70	77	84	91	98	98	99	99	100	100
114	22750	0	0	0	0	0	0	0	0	0	0	0	0	15	27	39	51	60	68	77	84	91	97	98	99	100
115	22800	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	29	40	48	58	67	75	83	90	96	100
116	22850	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	24	37	50	62	73	82	92	100
117	22900	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	25	41	56	69	86	100
118	22950	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25	48	74	100
119	23000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	45	100
120	23050	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

D. Summary and Conclusions

In summarization, adequate analytical expressions for % HP could not be derived from the Caterpillar data. An alternative approach was taken. That is, matrices were constructed with % throttle and rpm on the axes and % HP in the body. Knowing a % throttle and rpm value, a % HP value can be read directly from the matrix. A separate matrix was developed for both the Caterpillar model 1140 and 1160. Table 18 shows the resulting matrices.

The matrix approach does have some limitations. For instance, extrapolations were necessitated due to lack of data, particularly at rpm values less than 1200 rpm. Also, all motoring operation cannot be identified. Only closed throttle motoring is readily distinguishable. Although it is expected that most engine motoring is conducted at closed throttle, some part throttle motoring surely occurred. Consequently, the part throttle motoring will be assigned positive % HP values. This will be in error, however the magnitude of the error should be small.

In conclusion, a procedure for converting % throttle and rpm to %HP has been developed. The procedure does have some shortcomings, however these are considered minor. Many alternatives were considered in modeling %HP for the Caterpillar engines, and the matrix approach was considered the best.

APPENDIX 1

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

DATE: December 29, 1975

SUBJECT: Analysis of No-Load Rail Pressure Data for Cummins' Engines

FROM: Chester J. France, SDSB

TO: Gary Rossow, Project Manager, SDSB

This memo summarizes the analysis performed on various no-load rail pressure data for several Cummin's engines. Data for four engines were analyzed; NTC-390, NTC-350, and two NTC-290's. In addition, idle fuel pressure data for the Cummins' engines in the Los Angeles survey were analyzed.

The data for the NTC-390 and the two NTC-290's were gathered by EPA technicians at Yellow Frieght System terminal in Ypsilanti on December 1, 1975. The data for the NTC-350 were taken earlier on October 6, 1975. For each engine, rail pressure was measured for various rpm levels (idle to governed speed). The data gathered is summarized in Table 1.

The negative pressures for the NTC-390 and the two NTC-290's (see Table 1), immediately suggested that something was wrong. Cummins Engine Company engineers have told EPA personnel that based on their experience and data, idle and no-load rail pressure values should be always positive, although at low rpm's they may be small (2 to 3 psi). After some investigation, it was determined that the rail pressure transducer (Viatron pressure transducer) had experienced a zero shift due to temperature change. The transducer was calibrated at 72°F, while testing was conducted outdoors at a temperature of approximately 20°F. Although the transducer had a zero shift due to a temperature change, the linearity of the transducer was not affected. For engine to engine comparison, it was assumed that all engines at idle rpm, have the same fuel pressure.

The validity of the assumption that all Cummins engines have the same idle fuel pressure was substantiated by examining the idle fuel pressures for all of the Cummins engines in the Los Angeles survey. An underlying assumption was that the pressure transducers in Los Angeles did not experience zero shifts due to temperature changes. This seems reasonable since the pressure transducer calibrations and idle fuel pressure measurements were performed within an hour or two of each other. Temperature variations during the time between transducer calibrations and idle fuel pressure measurements would thus be minimal. Table 2 summarizes the idle fuel pressure data for the Cummins engines surveyed in Los Angeles.

The mean value of the idle pressure listed in Table 2 is 3.58 psi. The standard deviation of the idle pressure from the mean of 3.58 psi is 1.20 psi. Therefore, 95% of the idle fuel pressures will fall within $\pm$ 2.35 psi of the mean value. The Viation pressure transducer has a measurement accuracy of $\pm$ 3 psi, thus $\pm$ 2.35 psi ($\pm$ 1.96 x 1.20 psi) falls well within the accuracy of the transducer. The assumption that idle fuel pressures for Cummins' engines are the same is proven valid. Further, it would be quite reasonable to assume an idle fuel pressure of 3.58 psi for all Cummins engines surveyed in the CPAE-21 project.

Table 3 shows the data in Table 1 adjusted to an idle fuel pressure of 3.58 psi. The data appearing in Table 3, also is shown graphically in Figure 1. A multiple, stepwise regression was performed on this data with rail pressure as the dependent variable. Various powers of rpm were inputted into the regression analysis as possible independent variables. Only $rpm^{2.38}$ proved to be significant in the regression analysis. In summarization, the final form of the regression equation was:

$$\text{RAIL PRESSURE} = .1425 \times 10^{6}\ \text{RPM}^{2.38} + 2.9419$$

The multiple correlation coefficient was .9941 and the standard estimate of the error (standard deviation from the estimated curve) was .5324 psi. Thus, 95% of the data will fall within $\pm$ 1.0435 psi (1.96 x .5324 psi) of the predicted values for rail pressure. Again, $\pm$ 1.0435 psi falls within the measurement accuracy of the Viation pressure transducers.

The above equation demonstrates adequate accuracy for predicting no-load rail pressures for the Cummins' engines in the CAPE-21 survey. From an application viewpoint, the equation could be incorporated with ease into the heavy-duty cycle development program. It is therefore recommended that the following equation be used to describe no-load rail pressures:

$$\text{RAIL PRESSURE} = .1425 \times 10^{6}\ \text{RPM}^{2.38} + 2.9419$$

This equation would predict a rail pressure 3.6 psi for an idle rpm value of 618 (mean value of idle rpm for the engines in Table 3).

In conclusion, this equation would be used for all engines (trucks) in the CAPE-21 survey. Although the predicted values of idle rail pressure may not be identical to the actual values in Table 2, the analysis demonstrates that the predicted rail pressure values are well within the measurement accuracy of the pressure transducer.

Attachments (3)

Table 1. No-Load Rail Pressure Observed Data

Engine & Serial Number	NTC-290 (#10395479)		NTC-290 (#10525802)		NTC-350 (#10455480)		NTC-390 (#10411302)	
	RPM	Rail Press. PSI	RPM	Rail Press. PSI	RPM	Rail Press. PSI	RPM	Rail Press. PSI
	650	-3.4	600	-2.9	650	2.0	570	-3.3
	750	-3.4	750	-2.6	850	3.0	800	-2.6
	1000	-2.6	1000	-1.8	1000	3.8	1050	-1.8
	1250	-1.2	1250	- .8	1250	4.8	1300	0
	1500	1.8	1500	1.8	1500	6.3	1550	2.1
	1750	3.6	1750	3.2	1750	8.4	1800	4.9
	2000	6.6	2000	6.5	2000	10.9	2150	7.7
	2250	10.6	2200	9.1	2100	12.3	2300	9.7
	2300	11.6					2380	10.8

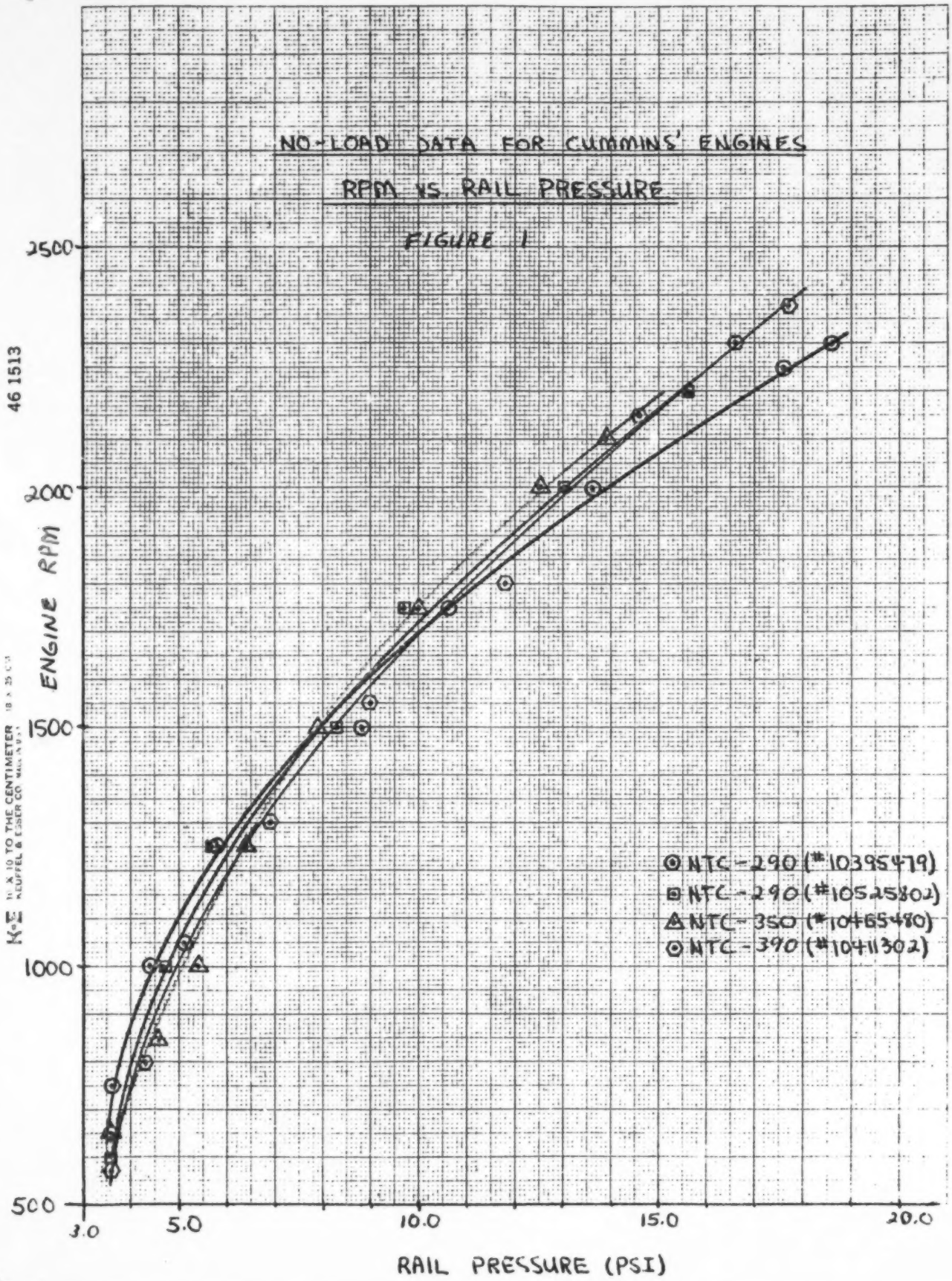
Table 2.

Truck Number	Fuel Pressure at idle (PSI)	Idle RPM
09	3.79	670
20	2.60	640
31	2.88	670
34	2.44	630
37	5.81	550
38	3.54	530
44	3.07	640
46	5.45	610
80	2.40	520
92	3.87	590
	Mean = 3.58 psi	Mean = 605 rpm

Table 3. No-Load Rail Pressure Data

W/Idle Rail Pressure of 3.58 PSI

Engine & Serial No.	NTC-290 (#10395479)		NTC-290 (#1052802)		NTC-350 (#10455480)		NTC-390 (10411302)	
	RPM	Rail Press. PSI	RPM	Rail Press. PSI	RPM	Rail Press. PSI	RPM	Rail Press. PSI
	650	3.6	600	3.6	650	3.6	570	3.6
	750	3.6	750	3.9	850	4.6	800	4.3
	1000	4.4	1000	4.7	1000	5.4	1050	5.1
	1250	5.8	1250	5.7	1250	6.4	1300	6.9
	1500	8.8	1500	8.3	1500	7.9	1550	9.0
	1750	10.6	1750	9.7	1750	10.0	1800	11.8
	2000	13.6	2000	13.0	2000	12.5	2150	14.6
	2250	17.6	2200	15.6	2100	13.9	2300	16.6
	2300	18.6					2380	17.7


NO-LOAD DATA FOR CUMMINS' ENGINES
RPM VS RAIL PRESSURE
FIGURE 1
46 1513
ENGINE RPM
2500
2000
1500
1000
500
3.0
5.0
10.0
15.0
20.0
RAIL PRESSURE (PSI)
NTC-290 (#10395479)
NTC-290 (#10525802)
NTC-350 (#10465480)
NTC-390 (#10411302)

EPA-AA-HDV 76-03

PB81-243172

Technical Support Report for Regulatory Action

"Engine Horsepower Modeling for Diesel Engines"

Chester J. France

October 1976

Notice

Technical support reports for regulatory action do not necessarily represent the final EPA decision on regulatory issues. They are intended to present a technical analysis of an issue and recommendations resulting from the assumptions and constraints of that analysis. Agency policy considerations or data received subsequent to the date of release of this report may alter the conclusions reached. Readers are cautioned to seek the latest analysis from EPA before using the information contained herein.

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Office of Mobile Source Air Pollution Control
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